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Water-Jet-Assisted Cutting

Proceedings: Bureau of Mines Open Industry Meeting, Pittsburgh, PA, June 21, 1984

Compiled by Charles D. Taylor and Robert J. Evans

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter
ft	foot
ft/h	foot per hour
ft•lb	foot pound
ft/lbf	foot pound force
ft/min	foot per minute
g/m^3	gram per cubic meter
gal	gallon
gal/min	gallon per minute
h	hour
hp	horsepower
Hz	Hertz
in	inch
(in•lbf)/in^3	energy/volume (relative measure of cutting efficiency)
in/r	inch per revolution
in/s	inch per second
kg	kilogram
kJ	kilojoule
kJ/m	kilojoule per meter
kJ/m^3	kilojoule per cubic meter
km	kilometer
kN	kilonewton
ksi	thousand pounds per square inch
kW	kilowatt
kW•h	kilowatt hour
kW/m^2	kilowatt per square meter
L/min	liter per minute
lb	pound
lb/ft^3	pound per cubic foot
lbf	pound force
lbf/in^2	pound force per square inch
m	meter
m^3/(kW•h)	cubic meter per kilowatt hour
m/min	meter per minute
m/s	meter per second
mg/m^3	milligram per cubic meter
min	minute
MJ/m^3	megajoule per cubic meter
mm	millimeter
mm/s	millimeter per second
μm	micrometer
MN/m	meganewton per meter
MPa	megapascal
pct	percent
psi	pound per square inch
psig	pound per square inch, gauge
r/min	revolution per minute
s	second
ton/h	ton (short) per hour
ton/min	ton (short) per minute
wt pct	weight percent

WATER-JET-ASSISTED CUTTING

Proceedings: Bureau of Mines Open Industry Meeting,
Pittsburgh, PA, June 21, 1984

Compiled by Charles D. Taylor[1] and Robert J. Evans[2]

ABSTRACT

Greater mining productivity requires a more efficient cutting process. The cutting force available from today's mining machines has been optimized with respect to machine size and weight. Researchers have shown that when employing water-jet-assisted cutting, bit forces and drum torques can be reduced significantly, which may allow mining machines to become lighter and more efficient.

The Bureau of Mines has initiated a program to develop a water-jet-assisted rotary cutting system using the conventional bit assisted by a directed water jet operating at moderate pressures (3,000 to 10,000 psi). This water-jet-assisted cutting system has the potential to improve cutting efficiency without increasing machine horsepower or water usage (beyond what is presently used for dust control) or requiring fundamental changes in mining practice. In addition to improvements in productivity, other anticipated benefits of water-jet cutting include reduced generation of respirable dust, elimination of frictional ignitions, increased bit life, reduced fines, and fewer machine vibrations.

The papers presented at this open industry meeting discuss the development of water-jet-assisted cutting technology and future application of this technology to a variety of mining techniques including roof drilling and longwall mining.

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[1] Industrial hygienist.
[2] Civil engineer.
Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

By John N. Murphy[1] and Bradley V. Johnson[2]

There have been numerous investigations relative to the use of high-pressure water jets to cut various materials; materials considered for this type of cutting process have ranged from relatively soft materials, such as coal, to harder substances, including granite and quartzitic materials. While there has been significant progress in this area and some notable successes for specific applications, many problems remain, including general system performance, erosion of jets at high pressure, jet stability, and the availability and reliability of rotating high-pressure seals.

Research conducted by the Bureau and by Bureau of Mines contractors has shown that the application of relatively low-pressure water jets, i.e., 5,000 to 20,000 psi, in conjunction with the classical mechanical cutting pick, gives significant increases in performance. Performance has been measured in a variety of ways, including reductions in the cutting forces required, the wear life of the mechanical cutter bit, reduced machine vibration, and reductions in generated dust and noise. While these enhancements are of direct benefit in terms of today's mining machinery, they offer the potential for the application of existing machines to more difficult mining conditions, e.g., hard roof, or alternatively higher production rates in less difficult strata, as well as the health and safety benefits of reduced dust and noise. Perhaps equally important are the future considerations in terms of machine design realizing the benefits of water-jet-assisted cutting; specifically, smaller, lighter, more mobile machines can be realized. The significant reductions in vibrations that have been observed to date also offer the opportunity for significant changes in the structural design of machines.

It has also been demonstrated, in a preliminary fashion, that the application of the low-pressure water jets can significantly reduce, or perhaps eliminate, concerns about frictional ignition from cutting picks impacting hard roof or pyritic inclusions.

As the proceedings of this Bureau of Mines-sponsored water-jet-cutting seminar will demonstrate, significant progress has been made in the understanding of the water-jet-assisted cutting process, the optimization of machine design parameters, and the field trials of various prototype machines utilizing water-jet-assisted cutting. The results to date have been extremely promising, which in part was the basis for this seminar, so that the industry could be aware of and utilize the progress made to date. However, more work is required before design engineers can successfully apply this promising technology to the machine of their choice. Ongoing Bureau work will certainly contribute toward the realization of this goal. These proceedings provide a realistic assessment of the current state of the art, and the bibliographic references with each article can provide additional information if required.

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[1] Research director, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

[2] Staff engineer, Division of Conservation and Development, Mining Research, Bureau of Mines, Washington, DC.

WATER-JET-ASSISTED ROCK CUTTING--THE PRESENT STATE OF THE ART

By Michael Hood[1]

ABSTRACT

The benefits of using moderate-pressure water jets to assist mechanical tools, notably drag bits, are reviewed. These benefits include reduced bit forces, especially the bit normal force; reduced bit wear; reduced dust make; and reduced incidence of frictional sparking. The research work that has been conducted to date to investigate this phenomenon has been largely empirical. Experiments are described that extend the data bank of this empirical knowledge. In addition, experiments aimed at gaining a better understanding of the fundamentals of the rock fragmentation process with this hybrid cutting method are outlined.

Results from the first of these experimental series are used to make recommendations as to the position of the jet with respect to the bit, the standoff distance between the nozzle exit and the bit-rock interface, and the jet energy. In addition, preliminary findings are reported regarding the increased jet energy necessary to maintain substantial reductions in the bit forces when the bit velocity is increased. Results from the second test series are discussed in the context of rock fracture behavior induced by mechanical tools acting alone. The likely influence of water jets on these fracture processes is analyzed. It is concluded that, in terms of the bit force reductions, a dominant effect of the jets when used in conjunction with sharp drag bits is continuous removal of the rock debris that forms ahead of the advancing bit. The observed reductions of bit wear and incidence of frictional sparking are attributed to reduced heat loading of the bit during the cutting operation. Reductions in the dust make are attributed to effective wetting of the fine rock particles before they become entrained in the airstream.

INTRODUCTION

Breaking rock from an in situ rock mass is carried out today using either a combination of mechanical tools (to drill holes) and explosives, or mechanical tools alone to cut the material from the face. It is evident that mechanical tools play a crucial role in what could be termed primary rock breaking, and it is instructive to review the principles by which these tools induce rock fracture.

First, the importance of rock breaking in modern western mining should be highlighted. About 8.5 million tons of ore and waste are mined each year in the United States alone (1).[2] Tunnel drivage each year by the countries of the Organization of Economic Cooperation and Development (OECD) is about 50,000 km. In the United States alone about 10,000 km of roadways are driven each year just in coal mines. Almost 2 pct of the total electric power generated in the United States, about 34 billion kW·h annually, is used in rock breakage processes. Admittedly, most of this energy is spent in secondary rock breaking, i.e., crushing and comminution, rather than in primary breaking from an in situ rock mass. However, these secondary processes also employ mechanical means to induce fracture. It should be noted the rock breaking processes are extremely inefficient. In primary processes, less than 10 pct of the energy supplied at the cutting bit generates new surface area, and in secondary processes, less than 1 pct of the applied energy is used to generate new surfaces (1). Thus, a conclusion may be drawn that vast quantities of material are extracted from the earth's crust each year and that this activity utilizes large quantities of energy.

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[1] Associate professor, Mining Engineering, University of California, at Berkeley, CA.

[2] Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

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MECHANICALLY INDUCED ROCK FRACTURE PROCESSES

A mechanical tool induces fracture in rock by the application of load through the tool to the rock. This load can be resolved into components acting normal and parallel to the rock surface. With some tools, for example, rolling cutters such as disc cutters and tricone bits, the normal force is the dominant component (fig. 1*A*). With other tools, for example, sharp drag bits, the parallel or cutting force is the dominant component (fig. 1*B*). The former may be described as an indentation process, and the latter as a cleavage process. Both of these techniques were used by stone age man.

Figure 2*A* shows the stress distribution in an elastic halfspace beneath a circular punch: the indentation case. Figure 2*B* shows the stress distribution in an elastic quarterplane with a line load normal to one of the surfaces: the cleavage case. Despite the differences in the way these loads are applied, the final result in terms of the mechanisms of crack propagation appears to be the same for both indentation and cleavage loading systems. In both cases chip formation occurs as a result of tensile crack growth. Tensile cracking ahead of

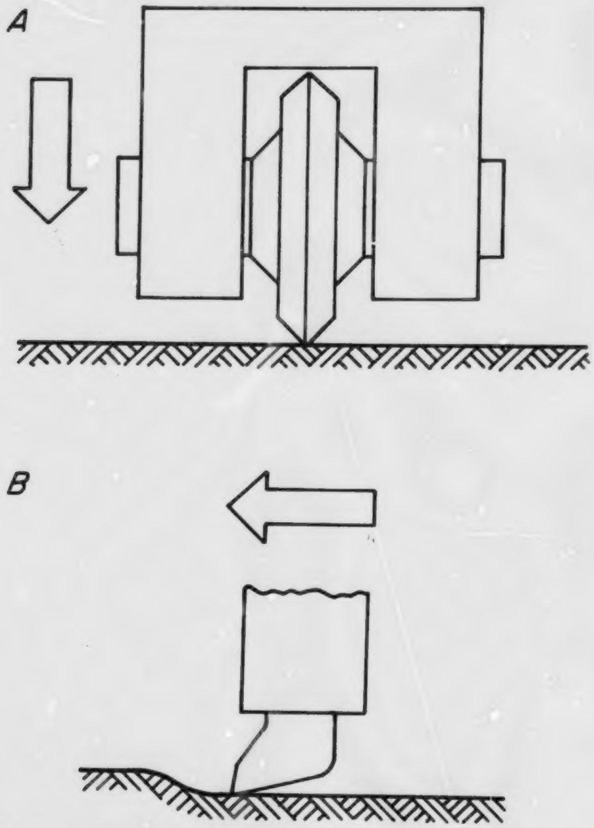

FIGURE 1. - Normal (*A*) and shearer (*B*) forces applied to induce rock fracture.

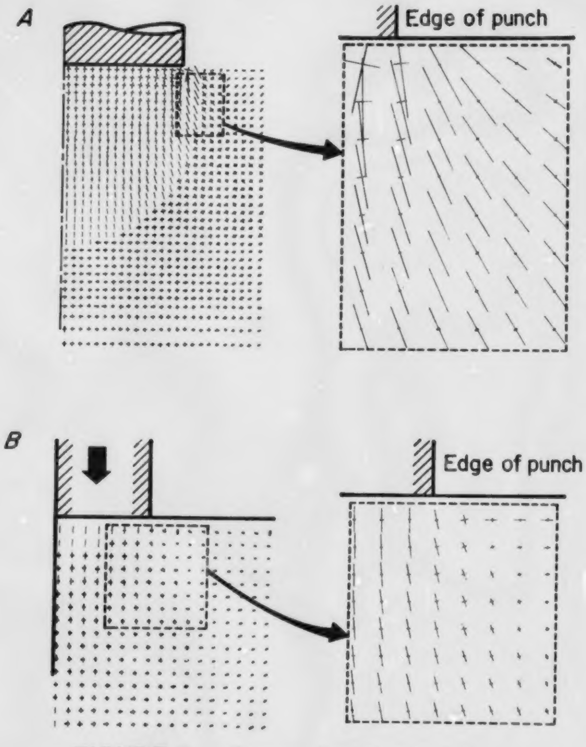

FIGURE 2. - Stress distributions for indentation (*A*) and cleavage (*B*) cases.

sharp drag bits was recognized by Evans and Murrell (2). More recent work (3-4) has shown that, although the stress field induced in the rock by an indenter is predominantly compressive, a tensile crack is initiated adjacent to the corners of the tool. This crack propagates initially in a Hertzian manner at some angle to the rock surface. Propagation of this crack then ceases, and the application of additional load results in failure by triaxial crushing beneath the tool. Subsequently a tensile crack, initiated towards the base of the Hertzian crack, propagates up to the surface to form a rock chip. The rock chips formed by both indentation and cleavage processes show a marked similarity, substantiating the claim that the final mechanisms of failure, i.e., crack growth, are identical. The relative inefficiency of the indentation process can be explained using this model in terms of the additional energy required to crush the rock beneath the tool in order to propagate the crack that forms the rock chip. Early man recognized that cleavage was the more efficient of the two breaking processes and used this method for forming arrowheads.

CURRENT ROCK BREAKING PRACTICE

The current state of the art is that most primary rock breaking is accomplished by drilling and blasting. In hard and medium-strength rocks, drill bits apply indentation loads to the rock to induce fracture. Only in weak rocks are rotary drills that induce fracture by cleavage employed. The reason that cleavage is selected as a breaking method only in a few rock cutting situations is the limited strength of the bit materials. Cemented tungsten carbide, which is used ubiquitously as a cutting edge for rock bits, is a brittle material. It has extremely high strength in compression but is relatively weak in tension. It is difficult to design bits to induce directly tensile (cleavage) fractures in rock without inducing tensile stresses in the tool material. Consequently, the loading arrangement usually configured is such that only compressive forces are applied to the bits and, by implication, compression forces (indentation loads) are applied to the rock.

The weakest rock types are mined today not by drilling and blasting but in a cutting operation, machining the seam or ore directly from the face. Coal mining serves as an example. The advantage of this approach is that it permits the cyclic drill-and-blast process to be replaced by a continuous operation. The cutting machine becomes one unit in a system that cuts and loads the ore at the face and transports it from the mine. These cutting machines usually employ bits that break the rock in a cleavage process. Present technology also permits continuous excavation for tunnel drivage of medium and even strong rocks. The machines in this case employ rolling cutters that break the rock by indentation. Excavation of these stronger rocks is feasible only where limited quantities of the rock are to be removed. Thus, at present, technology is not available for continuous excavation of these rock types for mining ore bodies, although there is considerable incentive in terms of increased productivity to achieve this goal.

The strength of the bit material, the tungsten carbide inserts, controls the upper limit on the power that is transmitted to the bits. This is true whether the loading method is cleavage or indentation. It will be shown theoretically and demonstrated in practice (fig. 3) that when the power at the bit exceeds a critical level, this results in rapid thermal deterioration of the bit insert, which quickly leads to bit failure. The specific power, i.e., the power required to excavate unit area of the rockface, is given by

$$P_s = E_s \times r$$

where P_s = specific power, kW/m^2,

E_s = specific energy, kJ/m^3,

and r = rate of excavation (face advance), m/s.

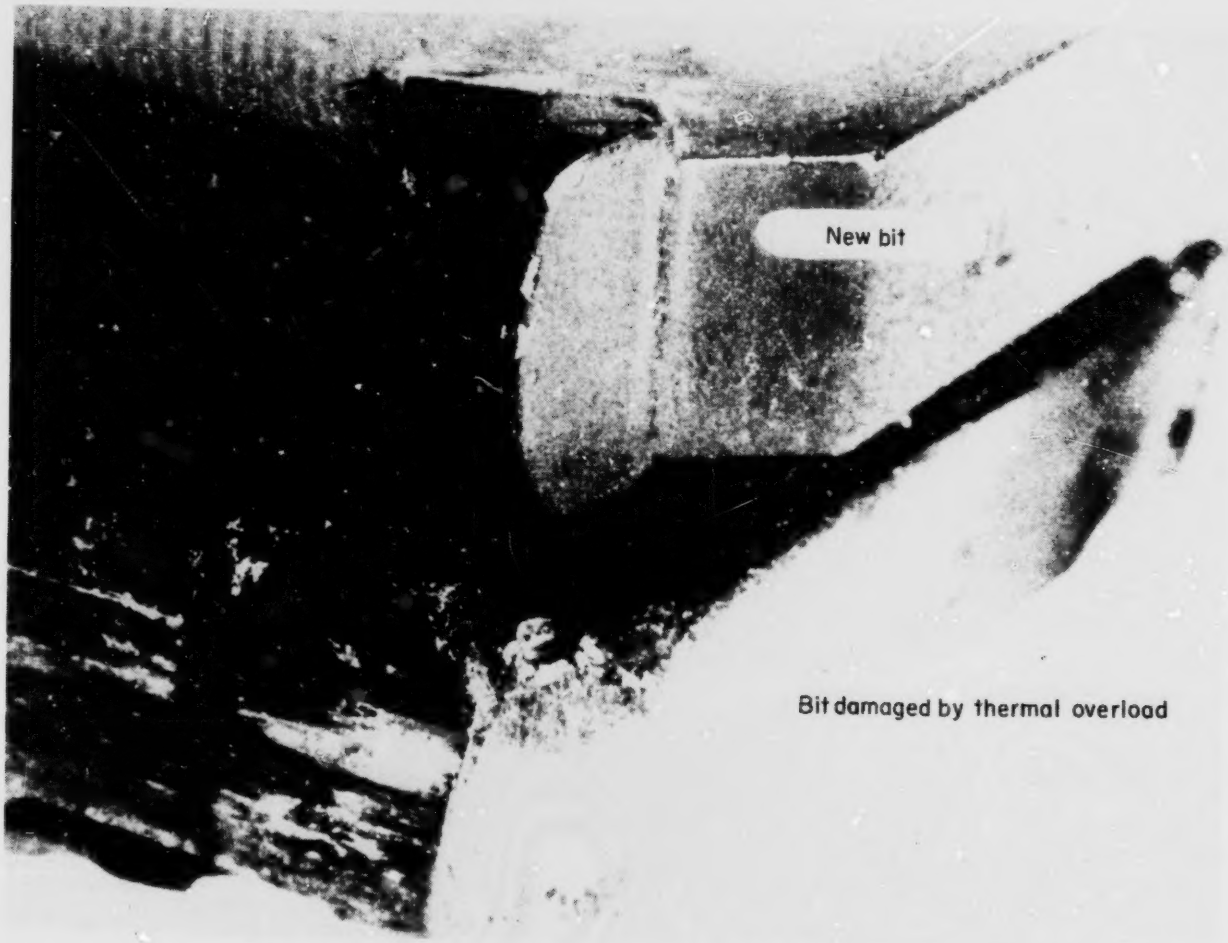

FIGURE 3. - Bit failure due to thermal deterioration.

Specific energy is defined as the energy required to remove a unit volume of rock from the face. Thus, this term is a measure of the efficiency of the rock breaking process. The specific energy of a given breaking process depends only on that process and the rock type. Furthermore, it has been noted that specific energy is related in an inverse power manner to the mean size of the rock fragments produced (fig. 4).

The following statements can now be made. First, from the expression above, it is apparent that since specific energy is a constant for a given breaking process, the rate of rock excavation is directly proportional to the power transmitted to the rock. If this power is to be transmitted only through cutting bits, then the fundamental limitation on the rate of rock excavation is the strength of the bit materials. Two approaches to overcome this limitation seem feasible. Either the strength of the bit material could be increased, or some of the power required to break the rock could be supplied by means other than through a cutting bit. The former approach is a problem for the materials scientist. An example of the latter approach is the use of explosives, placed in drilled holes, to cause rock fracture.

Second, from figure 4 it can be seen that explosives are an efficient means of rock excavation. Mechanical breaking methods--percussive and drilling, roller bit boring, and drag bit cutting--are moderately efficient processes. The inefficient techniques are the more exotic breaking methods: electron beam guns, lasers, flame jet piercing, and water jet erosion. These inefficient processes require several orders of magnitude more energy than explosives to break the rock. This result was, probably, the main finding to come from the flurry of research activity, conducted in the late 1960's and 1970's, into rock breaking processes (5-7). This work was conducted to determine the feasibility of applying these so-called exotic techniques for the purpose of rock excavation. In most cases it was found that, while technically feasible, the processes did not warrant further development because of the very large additional energy expenditures required.

Third, although the logarithmic relationship between particle size and energy has been known since the last century and various workers have ascribed empirical relationships to describe this behavior (8), a fundamental understanding of the rock fracture mechanisms that caused this phenomenon has yet to be derived. An improved understanding of these processes may well enable the development of more efficient rock breaking techniques.

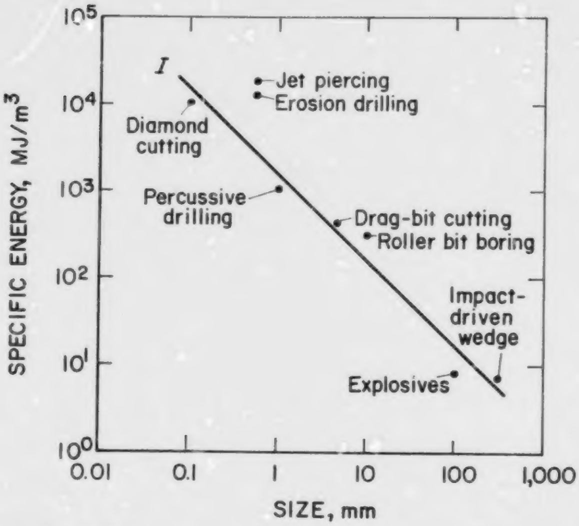

FIGURE 4. - Specific energy as a function of particle size for various rock-breaking processes.

THE DEVELOPMENT OF WATER-JET-ASSIST TECHNOLOGY

The development of a hybrid cutting system, using moderate-pressure water jets in combination with a mechanical tool, was inspired originally by a need to overcome a limitation alluded to above, i.e., thermal deterioration of the tool when power needed to achieve reasonable penetration rates was applied (9). In this application, drag bits were being used to cut in strong, abrasive rocks. It was discovered that suitably directed jets, at pressures less than 10,000 psi, would reduce the forces acting on the bit substantially. In the laboratory, cutting in norite, the bit cutting force was reduced by a factor of about three times (fig. 5*A*). Underground, cutting in quartzite, this force component was reduced about five times. Other results of equal significance from this test suite were the findings that the bit normal force was reduced even more dramatically than the bit cutting force (fig. 5*B*). Also, the bit temperatures were reduced substantially when the jets were employed.

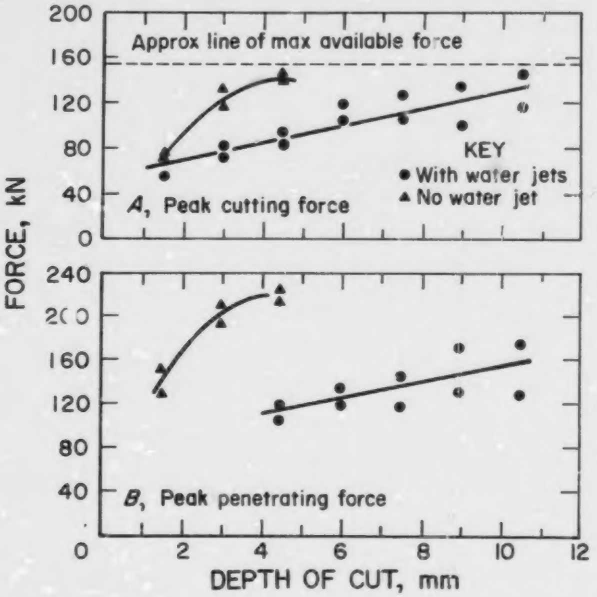

FIGURE 5. - Bit cutting (*A*) and normal (*B*) forces while cutting in norite with and without water-jet assist.

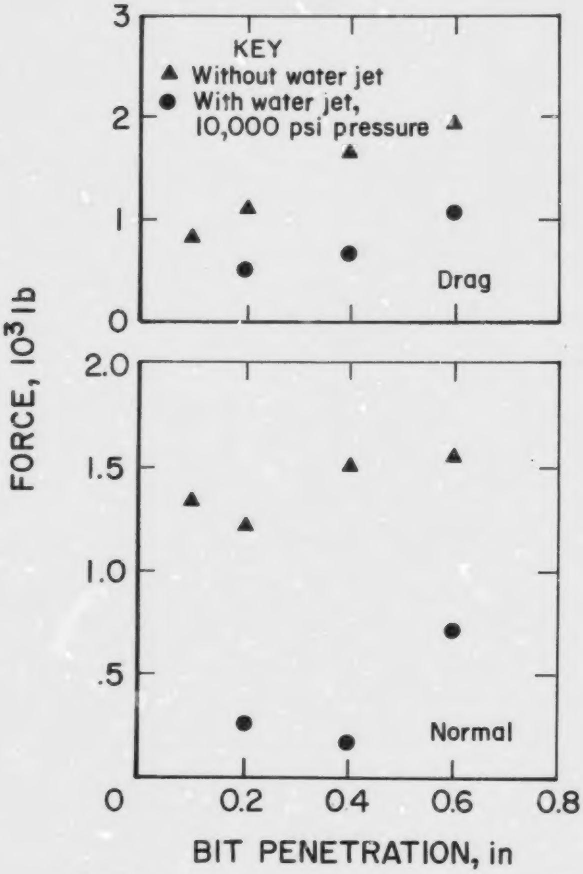

FIGURE 6. - Bit forces with and without jet assistance, cutting in Dakota sandstone.

Other workers (10-12) also using drag bits assisted by moderate-pressure water jets have cut a variety of medium and strong rocks. These researchers have found similar substantial bit force reductions when the jets are employed. Figure 6 gives the results of cutting in Dakota sandstone with and without water jets. It appears that in all cases at least a 40- to 50-pct reduction in the bit cutting force was realized. Also, the bit normal force was reduced more than the bit cutting force. A further substantial benefit from the use of these jets was revealed by Tomlin (12), who conducted his experiments on a roadheader mining machine at an underground test site. Using this machine it was discovered that the water jets have a substantial health and safety benefit in that they cause the dust make at the cutterhead to be reduced significantly. The water jets also decrease, and perhaps even eliminate, the incidence of frictional sparking.

IMPLICATIONS OF THE RESEARCH FINDINGS

The ability to reduce bit forces substantially overcomes the fundamental requirement of limiting power to the bit to prevent its deterioration. Thus drag bits now find application in rock types where previously the rock was considered too strong.

Many machines that employ drag bits as cutting tools are limited in terms of the maximum torque that they can exert at the cutterhead. Furthermore, it is found that the stresses imposed on the geartrains to the head are proportional to the torque to the fifth power, that is,

$$\sigma = T^5$$

where σ = stress,

and T = torque.

Thus, if the cutterhead torque is doubled, the stresses in the geartrain are increased by a factor of about 32 times. Conversely, of course, if the torque is halved, the stresses are reduced in like manner. The ability to reduce the bit cutting forces consistently by a factor of at least 2 implies that drum torques could be halved while the rate of mining is maintained. In some applications this has an obvious potential for improving machine reliability.

Bit failure often is induced by high normal forces acting on the carbide insert. The ability to reduce this force component even more dramatically than the bit cutting force component implies that the bit failure rate might be decreased substantially by the use of moderate-pressure water jets. This would have two consequences: (1) The direct cost of bits would be decreased, and (2) the time lost changing bits, which can be a significant portion of the overall downtime (13), would be reduced.

The ability to reduce bit temperatures while cutting also would substantially reduce the rate of bit wear and thus the bit failure rate. Significant reductions in bit temperatures have been reported when water jets are used despite the fact that the depth of cut has been increased to a value where the bit cutting force is the same with jets as without. Other evidence for substantial reductions in bit temperatures comes from field trials with a roadheader where workers report that the bits are cool enough to touch when they exit the cut. Why the bits are cooled to the extent reported is not clear. Calculations predict that the convective cooling effect of a jet would not significantly increase the heat transfer from the bit-rock interface. The model used in these calculations assumes that heat is generated by friction beneath the bit wearflat. It is assumed that the water contacts the leading face of the bit but does not penetrate beneath the bit wearflat. This second assumption is based on simple calculations that show that the pressure beneath the wearflat generally is greater, by an order of magnitude or more, than the pressure of these moderate-pressure jets. If the second assumption is in error and water does penetrate beneath the wearflat, then this could result in significant bit temperature reductions. Recent work by Friedman (14) on the fracture pattern left in a rock groove cut by a drag bit indicates a possible mechanism for trapping water in preexisting flaws ahead of the bit. This water then would be constrained beneath the wearflat with the forward passage of the bit.

The potential for a dramatic reduction in the incidence of frictional sparking, a major concern in gassy mines, is almost certainly a consequence of the reduced heat loads on the bit. The predominant cause of frictional ignitions and explosions in coal mines is sparking between the bits and the rock (15). Furthermore, the incidence of frictional ignitions continues to increase, reflecting the increase in mechanization (15). Ignitions occur in appropriate methane-air mixture when the energy level of a heat source is above a critical minimum level. The apparent substantial reduction in the heat levels generated within the bits when moderate-pressure water jets are used to assist the cutting operation would explain the observed reduction in ignitions.

Another safety and health hazard, which apparently is reduced substantially by the use of a water-jet-assist system, is mine dust. It is generally accepted that the primary source of dust in an underground mine where excavation is carried out using a cutting machine is the bit-rock interface. Past attention to controlling this hazard has concentrated on directing the airflow to move the dust particles away from the workers and installing scrubbers on machines to remove dust particles from the airstream. Despite considerable advances in these areas, directed mainly by the Bureau of Mines over the last 15 years, there probably is not one longwall coal face in the United States today that is in regular compliance with the very strict dust standards. This water-jet-assist approach appears to offer the potential for preventing small particles from becoming entrained in the airstream; that is, it may inhibit the generation of dust particles. This may herald a major advance in dust control since it is evident that inhibition of dust formation is a superior control strategy to dust suppression.

REMAINING TECHNOLOGICAL PROBLEMS

Despite the considerable promise of water-jet-assist technology, its application to mining machines has been slow. Two reasons for this can be found. First, current understanding of the mechanism by which the jets assist the breaking process is poor. It might be argued that such understanding is of academic interest only; after all, stone age man fashioned arrowheads without a grasp of the theories of fracture mechanics. However, an examination of the results of various workers (figs. 5-6) reveals that bit force reductions of factors of less than 2 to as much as 5 have been reported. Parameters that affect these force reductions include jet pressure, jet flow rate, jet position (with respect to the bit-rock interface), the standoff distance between the water jet nozzle and the rock, bit geometry, bit velocity, and rock type. Until recently the relative importance of these parameters in influencing bit force reductions has been unclear. Evidently, a machine designer needs guidance in this area in order to incorporate a water jet system onto a mining machine.

Second, although the jet pressures at which these systems operate are not high, some development of hardware to enable the jets to be channeled to the bits is required. This hardware includes a reliable swivel and a phasing system to ensure that only those bits actually in contact with the rock are assisted.

The following section addresses the first of these problem areas. The development of an hypothesis to describe a physical process follows one of two approaches. In the one approach a mathematical model of the process is proposed and experiments are conducted subsequently to verify the model. The alternate method is to conduct experiments first and to use the empirical data that are generated to derive the mathematical model. The latter approach has been adopted in this investigation. The work is not yet complete. The present study describes some key experiments which add to the data bank of empirical knowledge in this work area and which suggest physical processes by which the jets act to assist rock breakage.

EXPERIMENTAL PROCEDURES AND RESULTS

Experiments were conducted in the laboratory cutting the rock in a linear planing machine. These tests were carried out to determine the relative importance of the parameters listed above on the reduction of bit forces using water jets. To limit the experimental program to a manageable size, the parameters investigated were limited. Parameters not studied in this test series were bit geometry, rock type, depth of cut, and nozzle geometry. A V-faced chisel, or radial, pick was employed. All cutting experiments were conducted in Indiana Limestone. The properties of this rock are described by Krech (16). The depth of cut taken was 15 mm. The nozzle employed for the water jet used a 13° included angle convergent section and a parallel section at the exit. This design performed well in tests conducted by Leach and Walker (17). The parameters studied follow:

1. Jet position. Three jet configurations were examined (fig. 7):

   A. Two jets parallel to the leading face of the pick, about 1 mm ahead of this face.

   B. A single jet parallel to the leading face of the pick, aligned in the center of the tungsten carbide insert, again about 1 mm ahead of the face.

   C. A single jet directed behind the pick in the path of the pick.

2. Standoff distance. Using the optimum jet position (above), three standoff distances were examined: 25, 50, and 75 mm.

3. Jet pressure. A range of jet pressures up to a maximum of 10,000 psi was tested.

4. Jet flow rate. Three different nozzle diameters were tested in this test suite at jet pressures of 0.6, 0.8, and 1.0 mm. The flow rates corresponding to these nozzles at various pressures are given below.

5. Pick velocity. Two pick velocities were examined: 0.06 and 0.25 m/s.

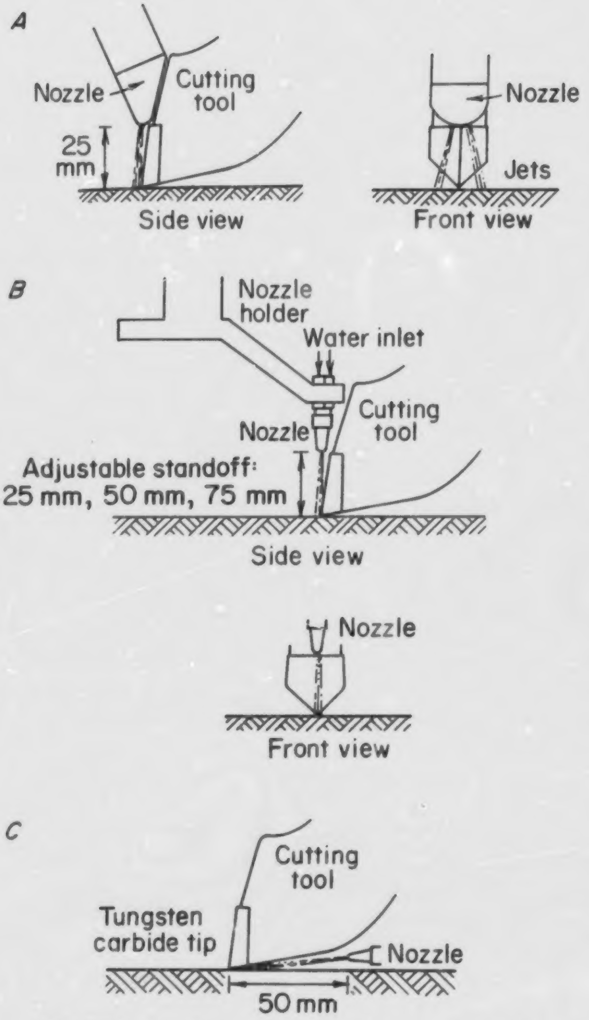

FIGURE 7. - Positioning of the jets with respect to the bit. *A*, Two jets ahead of the bit; *B*, single jet ahead of the bit; *C*, single jet behind bit.

JET POSITION

It was found that the optimal jet arrangement for this bit cutting in this rock type was a single jet directed 1 mm ahead of the leading face of the bit. The finding that the optimal jet position is ahead of the bit contradicts results reported by Ropchan (10) in which it is claimed that the greatest force reductions were achieved when a single jet was directed behind the bit. The major difference between the present investigation and the program conducted by Ropchan is the bit geometry. In the earlier study a point attack bit was used for the cutting experiments that employed water-jet assist. Only modest bit force reductions were reported when the water jet was directed ahead of the bit. It may be that the geometry of the point attack bit is not capable of exploiting fully the advantages of assistance with water jets.

It should be pointed out that previous work has shown that close proximity of the jet to the leading face of the bit is crucial to obtaining significant bit force reductions. If, during the cut, the jet strikes the rock 10 mm or even 5 mm ahead of the bit, its effectiveness in reducing the bit forces is decreased dramatically. On the other hand, it is important to insure that the jets do not strike the tungsten carbide insert because they cause rapid erosion of this insert. Accurate positioning of the jet with respect to the bit is a crucial factor in obtaining maximum benefit from the water jets.

STANDOFF DISTANCE

The standoff distance was found not to affect the bit force reductions provided that this distance was less than 100 times the jet nozzle diameter. However, at distances greater than this, the reduction in these forces fell rapidly. This finding should be qualified since, almost certainly, the result depends on the nozzle geometry and on the inlet conditions of the nozzle. The usefulness of this result probably is that it provides a rule of thumb for calculating an acceptable standoff distance. One justification for using this result is that it accords with other, more precise, laboratory measurements (17).

JET ENERGY

During the cutting operation the reductions in the bit forces were found to be affected both by the pressure at which the jet was operating and by the flow rate of the jet. However, careful analysis of the experimental data revealed that it was the combination of these two parameters, the jet power, that controlled these reductions. The results indicated that the magnitude of the reductions in bit forces is some function of the jet power normalized with respect to the bit velocity. This parameter has units of kilojoules per meter, or jet energy per unit length of cut. A typical curve for a slow cutting speed is given in figure 8. This result, in general, accords with intuition. It would be expected that, over a certain length of the cut, the bit force reductions would increase as the energy of the jet increased. In addition, it may be anticipated that these force reductions would reach a limit beyond which an increase in the jet energy would produce little or no effect. The results obtained indicate that these force reductions attain a maximum. When the normalized jet power is increased beyond this maximum, the bit force reductions again start to decrease. This behavior is not well understood.

BIT VELOCITY

The tests described above all were conducted at a pick velocity of 0.06 m/s. The maximum possible bit velocity in this test suite was constrained by the experimental apparatus to 0.25 m/s. Although this represents an increase in speed of a factor of 4, it still is about four times less than typical bit speeds on mining machines. Nevertheless, a comparison of tests conducted at these high and low laboratory bit velocities is of interest since it reveals the trend in the influence of jet parameters on bit force reductions.

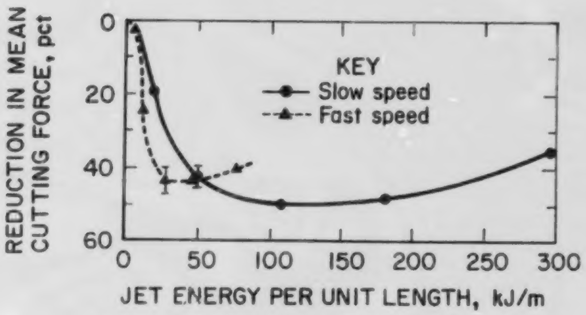

FIGURE 8. - Measured bit force as a function of the normalized jet power.

Results from experiments carried out at the higher bit speed of 0.25 m/s are also plotted as a function of normalized jet power in figure 8. Inspection of this curve shows that the trend observed previously for the lower speed tests, i.e., a rapid decrease in the bit forces with increasing jet energy up to some maximum jet energy, is reproduced at the higher bit speed. Moreover, visual inspection of these curves shows that their stationary points correspond to bit force reductions of about 50 pct at the low bit speed and about 45 pct at the high bit speed. The corresponding jet energies per unit length of cut are about 30 and 120 kJ/m, respectively. It might be concluded that provided that an appropriate energy is supplied to the jet, the bit force reductions are not affected significantly by changes in bit velocity. Furthermore, the jet energy appears to increase linearly with bit velocity.

However, closer inspection of these curves reveals that the maximum force reductions are not necessarily the optimum operating points. Because, in most cases, the rate of change of increase in force reductions slows at some fairly well defined point in the curve and the difference in force reductions between this point and the maximum is small, this point of change may be the most energy efficient point at which to operate the system. At present the analysis has progressed only to the point of identifying these optimum points by visual inspection. These are marked in figure 8. It can be observed that in this figure the normalized jet power changes by a factor of 2 while the bit velocity, as noted, changes by a factor of 4. This result was repeated using two other nozzle sizes.

Extrapolation of these admittedly limited data to calculate the probable jet power requirement for bits cutting at velocities of 1 m/s indicates that the jet power to an individual bit may be about 15 kW.

INVESTIGATION OF BREAKAGE MECHANISMS

An additional suite of experiments was performed. These experiments were designed specifically to throw light on the mechanisms of rock breakage when water jets at moderate pressures are employed to assist rock cutting with drag bits.

Three mechanisms by which the jets might act to reduce the bit forces were proposed:

1. Chemical attack of the rock by the water, i.e., stress corrosion cracking.
2. Initiation of a crack by the bit at low bit-force levels, and subsequent propagation of the crack by the water jet to form a chip ahead of the bit.
3. Effective clearance of the rock particles from the region adjacent to the bit.

STRESS CORROSION CRACKING

It is known that stress corrosion cracking (SCC) can produce significant reduction in the fracture strength of rock (18-20). However, the effectiveness of this approach in reducing fracture toughness decreases as the velocity of the crack front increases. This study was conducted to determine whether this mechanism could be effective when fractures are produced in a dynamic manner.

A series of high-speed films of the cutting operation was made using a film speed of 1,000 frames per second. Films were made both with and without the use of water jets to assist the cutting process. The approximate speed of crack propagation for the large rock chip that forms ahead of the bit was determined from careful viewing of these films. These chips typically were 80 mm in length and they were formed within one or, at most, two frames on the film. This implies a crack propagation velocity of about 80 m/s. Stress corrosion cracking is known to be a rate-dependent phenomenon, i.e., a unique relationship exists between the rate of change of crack length with respect to time and the stress intensity factor at the crack tip (21). Furthermore, there exists a limiting crack velocity beyond which stress corrosion plays no part in the fracture process. For most brittle materials, including rock, this limiting velocity appears to be of the order of 10^{-4} m/s to 10^{-1} m/s (21). Thus, the fracture velocity observed in these cutting tests is at least two orders of magnitude higher than the maximum velocity at which SCC could be invoked as a mechanism for reducing the fracture strength and thereby reducing the bit forces. Therefore, this hypothesis was rejected.

DRIVAGE OF CRACKS BY WATER PRESSURE

In addition to the large chip that is formed ahead of the bit in its forward passage through the rock, a large number of small rock chips also are created. A two-dimensional representation of this breakage process is shown in figure 9. Immediately after the formation of a large chip the depth of the cut seen by the bit is zero. As the bit continues its forward passage, the depth of cut increases and small rock fragments are broken ahead of the bit; these fragments are pushed ahead of the bit. Although details of the fracture process that produces these fragments still are not well understood, almost certainly a tensile crack is initiated in the rock adjacent to the corner of the bit between the leading bit face and the bottom surface of the bit for the case when the drag bit is sharp. In other words, it is a cleavage-type crack. On the other hand, when the drag bit is blunt, i.e., a wearflat exists because of a zero clearance angle between the bottom surface of the bit and the rock, then this tensile crack is initiated by indentation. In these processes it is known that crack initiation occurs with relatively low forces applied to the bit. A considerable increase in the bit force is required to cause this fledgling crack to propagate to form a rock chip.

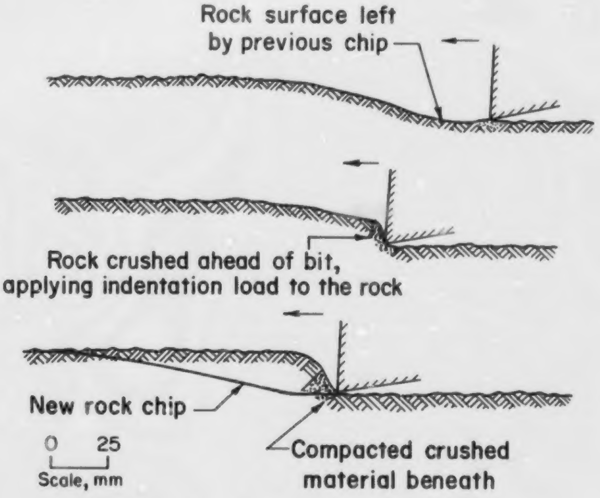
Rock surface left by previous chip
Rock crushed ahead of bit, applying indentation load to the rock
New rock chip
0 25
Scale, mm
Compacted crushed material beneath

FIGURE 9. - Chipping process ahead of sharp drag bit.

Thus, a plausible explanation for the influence of water jets in reducing bit forces is that the jet enters the crack initiated by and ahead of the bit, and the jet energy causes this crack to propagate to form a rock chip. Evidence supporting the mechanism of rock breakage was provided in a series of indentation experiments reported by Hood (22). In these tests rock specimens were loaded in a quasi-static manner in a series of punch tests with a blunt drag bit serving as the punch. It was found that when water jets were directed, at moderate pressure, onto the rock surface immediately adjacent to the bit, the force required to cause the rock to fail and a chip to form was reduced significantly. The explanation given for this reduced bit force was that full development of the fracture that produces the large rock chip ahead of the bit occurs only after the rock beneath the bit is crushed in an energy-consuming and inefficient process. By driving the crack with the water jet less crushing of the rock by the bit took place, and thus mechanical energy that normally would have been supplied by the bit was saved.

In the present test series the drag bit used was sharp and the purpose of this investigation was to determine whether a similar mechanism for crack drivage by water pressure was employed. It was argued that smaller quantities of finely crushed rock particles would be formed if jet pressure was responsible for driving the cracks that formed the major rock chips. Experiments were conducted in which all of the fragments produced during the cutting operation were collected. Size analyses of these particles revealed no discernible difference in the distribution of particle size with and without water jet assistance of the cutting process. A preliminary conclusion was drawn that the efficiency of the cutting process is not increased by crack drivage with water pressure when moderate-pressure jets are used to assist sharp drag bits. This conclusion must be regarded as tentative since the experimental technique used, analysis of the particle size, is not definitive. For example, although the quantity of fines was found to be the same in cuts made both with and without the use of water jets, the fines in the water-jet-assisted cuts may have been formed by erosion of the chip edges by the jets, while the fines in the dry cuts were produced by crushing.

CHIP CLEARANCE BY JETS

When water jets are not used during the cutting operation, the rock chips formed prior to the formation of a large chip are pushed ahead of the leading bit face. Therefore, stresses applied to the intact rock by the bit are transmitted through a region of crushed material. This material acts as a cushion, and the applied stresses are distributed more evenly and over a larger area than would be the case if no crushed material was present. This results in higher bit forces causing rock breakage.

Also, it is known that the strength of rock is increased dramatically by the application of confining pressure even when the confining pressure is small (23). The weight of the rock fragments that are pushed ahead of the bit in its forward progress through the cut is so small as to be negligible in terms of the confinement that it could provide. However, it is possible or even likely that this crushed material could be wedged between the front face of the bit and the inclined surface of the intact rock face (fig. 9). In this case appreciable confining pressure might be applied to the underlying rock, and thus the energy required to propagate a crack to form a rock chip would be increased. The likelihood of wedged rock fragments confining the rock in this manner would seem to be higher for bits with either zero or negative rake angles. Cutting experiments (24) have shown that bit forces indeed are increased as the bit rake angle changes from positive through zero to negative. Since the fracture process is tensile in all cases, this mechanism of confinement of rock particles may provide the explanation for these force differences.

Therefore, the hypothesis developed to explain the action of the jets in reducing bit forces was that they removed rock debris as it was formed ahead of the advancing bit. This would permit higher stresses to be applied to the rock by removing the cushion of crushed material. Also, any enhancement in rock strength as a result of confining stress applied through this debris would be removed.

Experiments were conducted to investigate the effect of confinement of rock particles ahead of an advancing drag bit. A plate fixture was mounted in front of the bit 25 mm above the rock surface (fig. 10). This plate prevented upward movement by the rock chips once the height of the debris in front of the bit exceeded 25 mm. In other words, this fixture caused the effect of confinement of the rock chips to be exaggerated. Tests were conducted both with and without the use of water jets assisting the cutting process.

Representative samples of the cutting force-time traces that were recorded both with and without the fixture and with and without the use of water jets are given in figures 11 and 12. Figure 11*A* shows the typical sawtooth trace obtained for a dry cut without the fixture. The cutting force increases from zero, or some low value, in an oscillatory but linear manner, up to a maximum. Beyond this maximum value the force decreases rapidly to

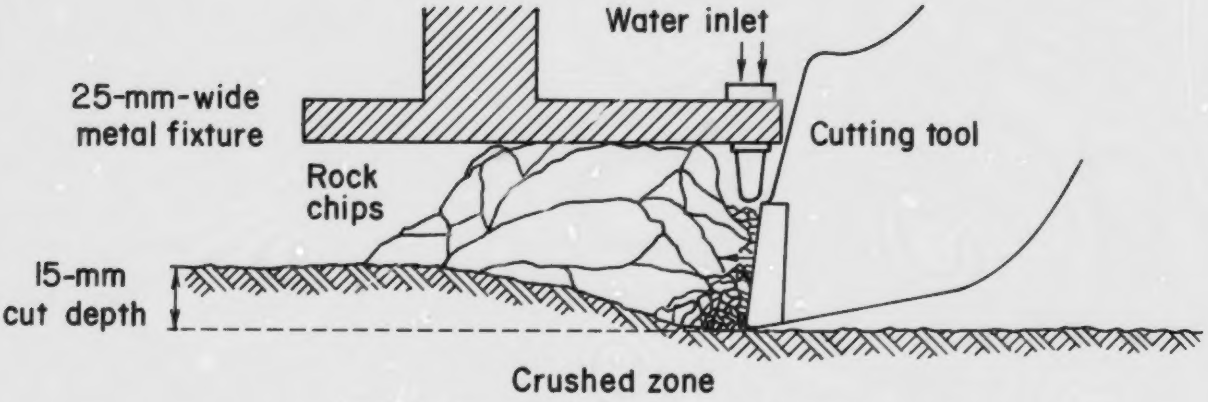

FIGURE 10. - Plate fixture ahead of drag bit.

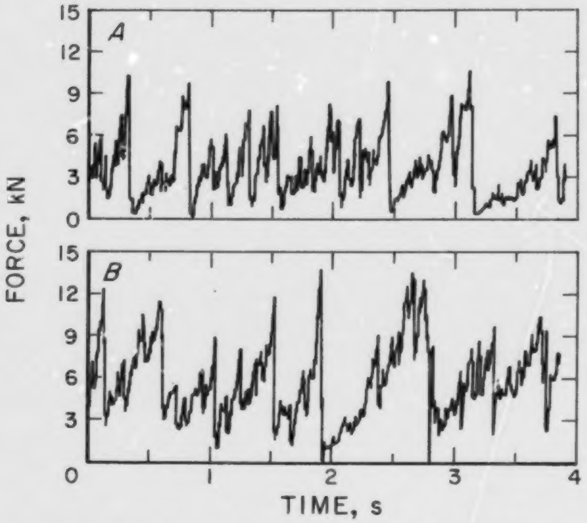

FIGURE 11. - Dry cuts without (*A*) and with (*B*) plate fixture.

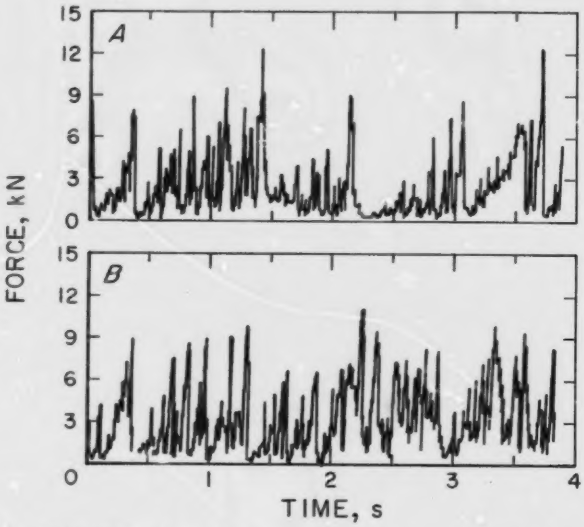

FIGURE 12. - Water-jet-assisted cuts without (*A*) and with (*B*) plate fixture.

a value close to zero, and the cycle is repeated. This characteristic signature is explained in terms of the observed chip formation process in front of the advancing bit (fig. 9). Immediately after a large chip is formed, the instantaneous depth of the cut is low or zero, and thus the bit cutting force is low or zero. As the bit advances it encounters a ramp formed by the bottom surface of the previous chip. Thus, the depth of cut that the bit sees increases, in an approximately linear fashion, from a value close to zero to the depth of cut predetermined in the experiment. The formation of small rock chips as this ramp is excavated together with crushing of those chips as they are pushed ahead of the bit accounts for the oscillatory nature of the trace. The force continues to increase because the depth of cut relative to the bit is increasing. At some point the pressure beneath the crushed material is sufficient to initiate and propagate another major chip. The instantaneous depth of cut ahead of the bit returns to a low value, and the cycle is repeated.

When the metal fixture was used for dry cuts, this same signature was repeated but it became much more exaggerated (fig. 11*B*). The area beneath each sawtooth oscillation, representing the mechanical energy required to form one large rock chip, is much increased.

The equivalent traces without and with the metal fixture mounted ahead of the bit but with water-jet assistance are given in figures 12*A* and 12*B*, respectively. A notable feature of these plots is that although saw-tooth oscillations still can be distinguished, in general, they are of short duration so that the area under the curves, and thus the expenditure of mechanical energy, is small. Little difference can be observed by visual inspection of these plots. This small difference is reflected in the relatively small difference in the measured cutting forces when jets were used. These forces for this set of experiments are given in table 1. The mechanical energy supplied to the bit in these experiments is given in table 2.

TABLE 1. - Bit forces with and without metal plate, kilonewtons

	With plate	Without plate
With water jets:		
Mean....................	2.95	2.24
Mean peak...............	7.99	6.82
Without water jets:		
Mean....................	6.63	3.94
Mean peak...............	12.40	8.45

TABLE 2. - Mechanical energy supplied to the bit, kilojoules

	With plate	Without plate
With water jets..........	3.47	2.62
Without water jets.......	7.76	4.62

High-speed films made of the cutting operation when water-jet assistance was employed showed that rock particles were removed from the region ahead of the bit immediately after they were formed. This contrasts with evidence from similar films made of the cutting operation when water jets were not used, which indicated that rock chips were carried ahead of the bit for the complete length of the cut. Further evidence as to the effectiveness of this flushing operation using jets was provided by examination of the groove after the bit had passed. With dry cuts this groove bottom was packed with finely crushed material which obviously had been forced and/or trapped beneath the bit wear-flat. With water-jet-assisted cuts this groove bottom contained no crushed material.

DISCUSSIONS OF FINDINGS AND CONCLUSIONS

The experimental evidence supports the hypothesis that the dominant mechanism by which moderate-pressure water jets act to assist the rock cutting process using sharp drag bits is by effective chip clearance from the region ahead of the bit. Removal of these rock particles causes a reduction in the measured bit forces because the stresses transmitted to the rock by the bit are increased for a given bit load. In addition, the confining stress that may be applied by these rock particles to the intact rock when cutting dry is removed. This also would cause a reduction in the bit forces necessary to excavate the rock.

It was noted above that in order to reduce bit forces substantially it is important that the jet be positioned within 1 or 2 mm of the leading face of the bit. The necessity for this accurate positioning of the jet was provided by the high-speed films of the cutting operation. When jets are not used, platelike particles form and are pushed ahead of the bit. If the jet is directed too far ahead of the leading bit face, it strikes the center of one of these particles and the jet energy, which is insufficient to damage the rock, is dissipated harmlessly. On the other hand, when the jet is directed immediately adjacent to the leading bit face, it penetrates beneath the edge of these particles and the energy dissipated as it strikes the intact rock ahead of the bit lifts and removes all debris in this region.

The experimental finding that jet energy does not have to increase linearly with bit velocity is consistent with this hypothesis for jet assistance, i.e., that the dominant influence of the jets is removal of broken material from ahead of the bit.

Another possible mechanism by which the jets may assist the cutting process is crack drivage by jet pressure. Apparently this does occur with blunt bits and may or may not take place with sharp bits; the experimental results are unclear. The third possibility for reducing bit force as examined in this study was stress corrosion cracking. Apparently this does not influence the breakage process.

A substantial reduction in bit temperatures by the use of water jets is not predicted by theory if the assumption is made that the dominant mode of heat transfer is convective and that cooling takes place from the leading bit face. However, laboratory and field tests have shown that bit temperatures are reduced substantially when jets are used. Whatever the flaw in the mathematical model, the fact that heat loads to the bit during the cutting operation are significantly decreased when jets are used almost certainly accounts for the observed dramatic reduction in frictional sparking. Furthermore, this finding, taken together with reduced bit normal force that is observed even when the depth of cut is increased so that the bit cutting force is not decreased, probably accounts for the reported reductions in bit wear and breakage.

Dust might be defined as those fine particles that become entrained in the air. On a coal face it is known that dust accounts for only a very small fraction of the fine particles that are generated during the cutting operation. Results from these experiments indicate that the quantity of fines produced is not different when water jets are used. However, measurements show that dust quantities at the face are reduced substantially when jets are used to assist the cutting process (12). Thus, it must be assumed that the effect of the jets is to wet the fine particles as they are produced at the face before they become entrained in the ventilation airstream. This assumption is consistent with the model proposed in this paper to describe the dominant effect of the jets on the rock fracture process, i.e., that the jets act to flush chips and rock debris from the region ahead of the bit. For this flushing operation to be most effective, the jet is aimed directly at the small region where the rock particles, both small and large, are initiated. Thus, before these particles are removed from the face they have been wetted by the jet. These wetted particles are much less likely to become entrained in the airstream.

Another factor with a high potential for achieving even further reductions in the dust make is the possibility of redesigning the cutting machine to take deeper cuts at lower bit velocities. It has been known for decades that fewer fines are produced by deep, widely spaced cuts (25). It is known also that the entrainment process has much to do with bit, or drum, velocity. The problem with putting this knowledge into practice on mining machinery has been that this cutting method places high unbalanced loads on the drum and that high drum torque is needed. Water-jet assistance offers the potential for overcoming these difficulties.

The other research results are summarized as follows. Parameters influencing the effectiveness of water jets in reducing bit forces were examined. It was found that the optimal jet position for assisting a sharp chisel bit was immediately ahead of the leading face of the bit. The jet should strike the rock no more than 1 or 2 mm ahead of this face. The standoff distance will depend on the nozzle geometry and the nozzle inlet conditions. It was found in these tests that the nozzle exit should be within 100 nozzle diameters to be most effective. Although jet pressure and jet flow rate both affect the reduction in the bit forces, the jet power per unit length of cut was found to be the parameter that controlled the magnitude of these force reductions. The optimal value of this normalized jet power parameter was found to depend on bit velocity. An extrapolation from limited experimental data yielded an estimate for the jet power of 15 kW per bit for bit velocities of about 1 m/s.

REFERENCES

1. National Research Council, National Materials Advisory Board. Comminution and Energy Consumption. Natl. Acad. Press, Publ. NMAB-36, 1981, 283 pp.

2. Evans, I., and S. A. F. Murrell. Wedge Penetration Into Coal. Colliery Guardian, v. 39, No. 455, Jan. 1962, pp. 11-16.

3. Hood, M. Phenomena Related to the Failure of Strong Rock Adjacent to an Indenter. J. S. Afr. Inst. Min. and Metall., v. 78, No. 5, Dec. 1977, p. 113.

4. Cook, N. G. W., M. Hood, and F. Tsai. Observations of Crack Growth in Hard Rock Loaded by an Indenter. Int. J. Rock Mech. and Min. Sci., v. 21, No. 2, 1984, pp. 97-107.

5. Liessmann, Y. Das Mikrowellenverfahren zur Zerkleinerung von Gesteinverschusanlage und Erzielten Ergebrisse (The Microwaves for Rock Breaking--Experimental Techniques and Results). Bergbautechnik, v. 16, No. 10, 1966, p. 537.

6. Carstens, J. P. Thermal Fracture of Rock--A Review of Experimental Results. Paper in North American Rapid Excavation and Tunneling Conference, ed. by K. S. Lane and L. A. Garfield (Proc. Conf., Chicago, IL, June 5-7, 1972). AIME, 1972, pp. 1363-1392.

7. Summers, D. A., and D. J. Bushnell. Preliminary Experimentation of the Design of the Water Jet Drilling Device. Paper E2 in Third International Symposium on Jet Cutting Technology (IIT Res. Inst., Chicago, IL, May 11-13, 1976). BHRA Fluid Engineering, Cranfield, Bedford, England, 1976, pp. E2-E21.

8. Bond, F. C. Third Theory of Comminution. Trans. AIME, v. 193, 1952, pp. 484-494.

9. Hood, M. Cutting Strong Rock With a Drag Bit Assisted by High Pressure Water Jets. J. S. Afr. Inst. Min. and Metall., v. 77, No. 4, Nov. 1976, pp. 79-90.

10. Ropchan, D., F. D. Wang, and J. Wolgamott. Application of Water Jet Assisted Drag Bit and Pick Cutter for the Cutting of Coal Measure Rocks (U.S. Dep. Energy contract ET-77-A-01-9082, CO Sch. Mines). Apr. 1980, NTIS DOE/ET/12463-1, 120 pp.

11. Dubugnon, O. An Experimental Study of Water Assisted Drag Bit Cutting of Rocks. Paper in First U.S. Water Jet Symposium (Golden, CO, Apr. 7-9, 1981). CO Sch. Mines Press, Golden, CO, 1981, pp. II-4.1 to II-4.11.

12. Tomlin, M. G. Field Trials With 10,000 psi Prototype System. Paper in Seminar on Water Jet Assisted Roadheaders for Rock Excavation (Pittsburgh, PA, May 26-27, 1982). U.S. Dep. Energy and U.K. National Coal Board, 1982, pp. C1-C11.

13. Pimental, I. R. A., J. T. Urie, and W. J. Douglas. Evaluation of Longwall Industrial Engineering Data (U.S. Dep. Energy contract ET-77-C-01-8915, Ketron Inc., Wayne, PA). 1981, 11 pp.; NTIS DOE/ET/12532-T2.

14. Friedman, M. Analysis of Rock Deformation and Fracture Induced by Rock Cutting Tools Used in Coal Mining (U.S. Dep. Energy contract AC04-76DP00789, Texas A & M Univ., College Station, TX). Sandia National Laboratory, Albuquerque, NM, Contractor Rep. SAND 83-7007, Mar. 1983, 36 pp.

15. Richmond, J. K., G. C. Price, M. J. Sapko, and E. M. Kawenski. Historical Summary of Coal Mine Explosions in the United States, 1959-81. BuMines IC 8909, 1983, 53 pp.

16. Krech, W. W., R. A. Henderson, and K. E. Hjelmstad. A Standard Rock Suite for Rapid Excavation Research. BuMines RI 7865, 1974, 29 pp.

17. Leach, S. J., and G. I. Walker. The Application of High Speed Liquid Jets to Cutting; Some Aspects of Rock Cutting by High Speed Water Jets. Proc. R. Soc. London, Ser. A, v. 260, 1966, pp. 295-308.

18. Hoagland, R. G., G. T. Hahn, and A. R. Rosenfield. Influence of Microstructure on Fracture Propagation in Rock. Rock Mech., v. 5, 1973, pp. 77-106.

19. Westwood, A. R. C. Control and Application of Environment Sensitive Fracture Processes. J. Mater. Sci., v. 9, 1974, pp. 1871-1895.

20. Schmidt, R. A. Fracture Mechanics of Oil Shale; Unconfined Fracture Toughness, Stress Corrosion Crackling, and Tension Test Results. Paper in Energy Resources and Excavation Technology (Proc. 18th Symp. on Rock Mechanics, Keystone, CO, June 22-24, 1977). CO Sch. Mines Press, Golden, CO, 1977, pp. 2A2-1 to 2A2-6.

21. Barton, C. C. Variables in Fracture Energy and Toughness Testing of Rock. Paper in Issues in Rock Mechanics (Proc. 23d U.S. Symp. on Rock Mechanics, Univ. CA--Berkeley, Aug. 25-27, 1982). Society of Mining Engineers, AIME, 1982, pp. 449-462.

22. Hood, M. A Study of Methods To Improve the Performance of Drag Bits Used To Cut Hard Rock. Ph.D. Thesis, Dep. Min. Eng., Univ. Witwatersrand, Republic of South Africa, 1978, 150 pp.; available from M. Hood, Univ. CA, Berkeley, CA.

23. Jaeger, J. C., and N. G. W. Cook. Fundamentals of Rock Mechanics. Chapman and Hall, London, 3d ed., 1979, 593 pp.

24. Roxborough, F. F. Cutting Rocks With Picks. Min. Eng. (London), v. 132, No. 153, June 1973, pp. 445-455.

25. Barker, J. S., C. D. Pomeroy, and D. Whittaker. The M.R.E. Large Pick Shearer Drum. Min. Eng. (London), v. 125, No. 65, Feb. 1966, pp. 323-333.

ANALYSIS OF MECHANICAL TOOL FORCE REDUCTIONS WHEN USING WATER-JET-ASSISTED CUTTING

By R. J. Evans,[1] H. J. Handewith,[2] and C. D. Taylor[3]

ABSTRACT

Water-jet-assisted cutting is the synergistic combination of a mechanical pick and a directed moderate-pressure water jet which greatly facilitates the cutting process. The water jet assists the mechanical pick by lubricating the cutting process, by cleaning the crushed zone directly in front of the bit to reduce friction, by cooling the mechanical tool to improve bit life, and by exploiting cracks close to the bit to promote chip fragmentation.

An In-Seam Tester, which is a hydraulically activated single pick instrumented to measure and record cutting forces, was designed and fabricated by the Bureau of Mines to obtain design data for a rotary drum cutting system using moderate-pressure jets (3,000 to 10,000 psi). Data are presented for cutting trials in a simulated coal block, underground in the Pittsburgh coal seam, and on test blocks of sandstone and limestone for water-jet-assisted and dry cutting. Data are presented which indicate that pick forces are significantly reduced when using water-jet-assisted cutting.

BACKGROUND

The last major breakthrough in coal mining cutting tool technology was in the 1940's, when the introduction of tungsten carbide significantly increased the life and cutting ability of mechanical tools. Recent studies with water-jet-assisted cutting indicate that significant improvements can be made to the cutting process by using this new technology.

Using conventional cutting technology, today's coal mining machines, such as the continuous miner and longwall shearer, have generally been optimized with respect to their cutting ability in relation to their size and weight. When cutting, these machines must accept high reactive torque and thrust forces. The ability to react to these forces is a function of the machine's weight and tractive effort. Attempts to increase thrust and torque have resulted in increased machine weight and size, thereby decreasing machine maneuverability and productivity.

The potential for a major advance in cutting technology has been indicated by researchers using water-jet-assisted cutting systems. Experiments have been conducted in a wide variety of rock types (both in the laboratory and underground) that demonstrate substantial improvements in cutting performance along with significant improvements in health and safety. These improvements include significant reductions in pick cutting and normal forces; improvements in bit life, with substantial reduction in failures of the tungsten carbide inserts; reduction in fines; significant reductions in dust; and reduction of frictional ignitions.

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[1] Supervisory civil engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

[2] Project research supervisor, Boeing Services International Inc., Pittsburgh, PA.

[3] Industrial hygienist, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

APPROACH

The Bureau of Mines is currently pursuing a program to develop a water-jet-assisted rotary cutting system that can be used for a longwall shearer or a continuous miner. This system will use water-jet pressure ranging from 3,000 to 9,000 psi, without increasing current water usage or significantly increasing total power consumption. Research has shown that water-jet-assisted cutting has the potential to reduce machine thrust and torque when compared to conventional cutting. The limits of this study are shown in figure 1 bounded by the shaded area. Previous researchers explored this new technology through laboratory testing of coal and coal measure rock for fracture properties but fall short of the desired goal to predict mining machine performance, component wear, and costs. The approach adopted here was to use an In-Seam Tester to find the relationships between dry and water-jet-assisted

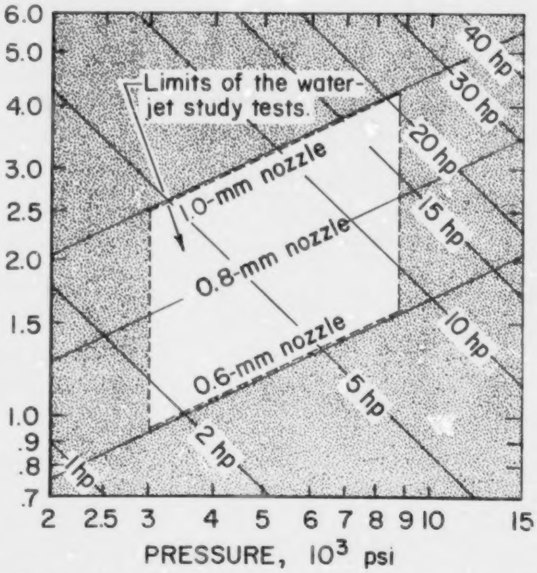

FIGURE 1. - Water-jet study range of force and flow rate parameters.

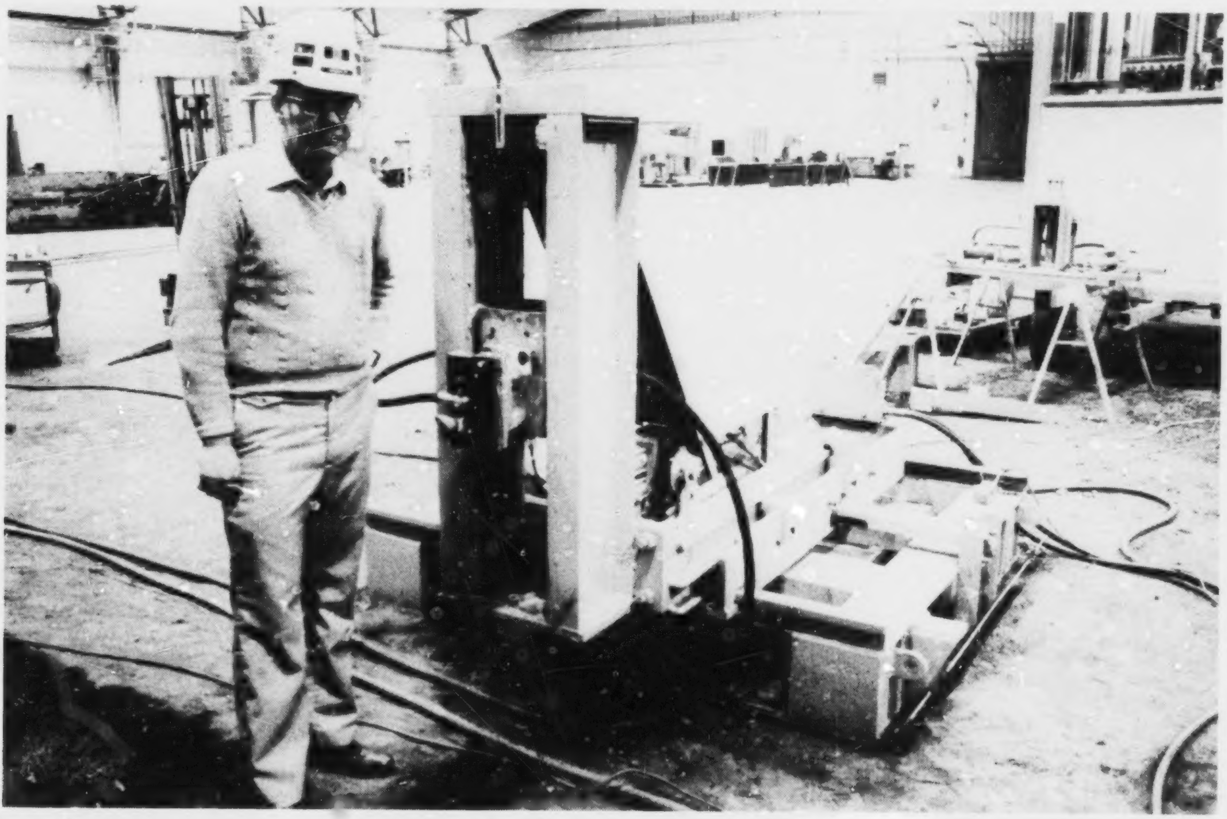

FIGURE 2. - Heavy-duty In-Seam Tester.

cutting in coal and coal measure rocks. The In-Seam Tester (fig. 2) is a hydraulically powered single pick that cuts upward in a linear plane at 25 ft/min. The pick is instrumented with a four-pillar dynamometer to measure and record the orthogonal cutting forces as illustrated in figure 3.

The rationale for using an In-Seam Tester is that one of the major difficulties facing investigators conducting laboratory coal cutting tests is to ensure that the relatively small samples being cut are representative with respect to the confined ground-induced stresses. This is more of a problem with coal than other rock types because of cleat and joint presence in the coal mass and dehydration and temperature changes that occur when blocks of coal are removed from the mine. The In-Seam Tester will allow use of full-scale tools to avoid potential errors in force scalar relationships.

Cutting tests were made on coalcrete, underground in the Pittsburgh coal seam, and on blocks of limestone and sandstone. Properties of these materials are shown in table 1. Coalcrete (cement, flyash, and coal) is a synthetic coal block that is cast in place to simulate coal properties.

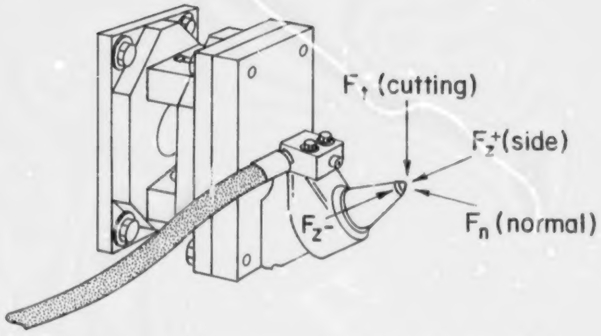

FIGURE 3. - Force reactions on a cutting bit.

Two cutting tools were tested: the longwall flat pick and the conical bit (fig. 4). Each cutting tool was tested with and without water-jet assist using a front-mounted water jet that impinges directly in front of the cutting tool using three pressure ranges: 3,000, 6,000, and 9,000 psi.

The orthogonal bit forces were measured with a four-pillar dynamometer that was designed and fabricated at the Pittsburgh Research Center. One inherent feature of the dynamometer is that it is more sensitive to side and cutting forces than it is to normal force.

The water-jet nozzles were made from stainless steel, 3/8-in-diam hexagonal socket head screws, which were machined down to an internal Leech and Walker configuration. Three nozzle exit diameter sizes (0.6, 0.8, and 1.0 mm) were used (fig. 1).

TABLE 1. - Material properties and test results

Item	Berea sandstone	Indiana limestone	Coalcrete block	Pittsburgh seam coal
Density....................lb/ft..	130	145	106	85
Porosity......................pct..	1.98	14.1	NA	NA
Unconfined strength, psi:				
Compressive.....................	8,300	4,700	898	NA
Shearer.........................	NA	NA	132	NA
Hardgrove grindability index......	NA	NA	62	58
Cutting force with flat bit, lbf:				
Dry.............................	3,620	NA	350	450
Wet[1]............................	1,695	NA	380	390
Cutting force reduction......pct..	53	NA	Neg	Neg
Depth of cut.................in..	1	1	1.5	1.5
Bit spacing..................in..	2	2	3	3

NA Not available. Neg Negligible.

[1] Using 3,000-psi water jets with 0.015-in-diam jet nozzle.

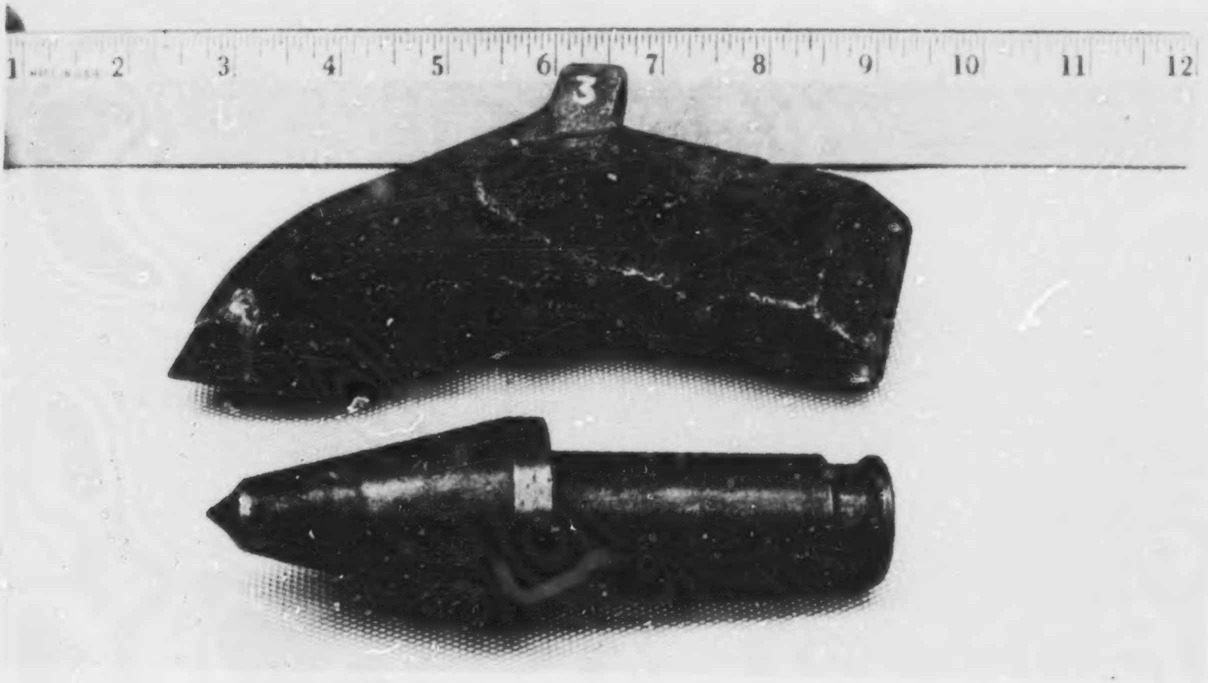
1
2
3
4
5
6
7
8
9
10
11
12
3

FIGURE 4. - Flat and conical cutting bits.

Each cutting test with the In-Seam Tester consisted of data from 140 in of rock-coal cutting. The cutting stroke on the Tester is 14 in. Each cut had 10 in of steady-state cutting data recorded. The typical cutting sequence progresses from left to right with 3-in spacing between each cut. The depth of cut ranged from 1 to 2 in, depending on the spacing and cutting material, as shown in figure 5. After each test, a cleanup cut was made, progressing from right to left, using half spacing that cut between each groove of the previous cut.

Dust measurements for dry and wet cuts were made during operation of the In-Seam Tester. Dust levels were measured during cutting by drawing air near the cutting tool through a duct connected to a dust box. A vacuum pump was used to draw dust from the cutting surface into the duct and through the dust box. Two cyclones were placed inside and near the middle of the box, connected to tubing that carried dust from the cyclones to sampling instruments located outside the sampling box.

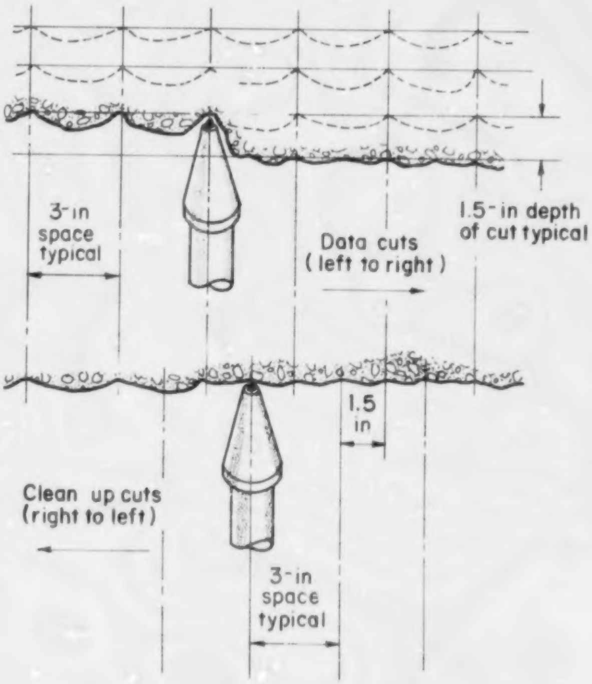
3-in space typical
Data cuts (left to right)
1.5-in depth of cut typical
Clean up cuts (right to left)
1.5 in
3-in space typical

FIGURE 5. - Cutting sequence of coal face.

RESULTS

Water-jet-assisted cutting is the synergistic combination of a mechanical tool and a directed high-pressure water jet. The high-pressure jet exploits any cracks in the vicinity, lubricates the cutting process, increases bit life, and reduces dust and incidence of frictional ignition. Water jets are especially effective when cutting a granular texture like sandstone.

Tests conducted on Berea sandstone, with properties as shown in table 1, demonstrated a 53-pct reduction in net cutting force and a peak force reduction of 39 pct when using a conical bit and a 0.015-in-diam jet nozzle with 3,000-psi pressure. These tests were conducted at a 1-in depth of cut and 2-in spacing and compare very favorably with reported results.[4]

When cutting softer materials such as coalcrete and Pittsburgh seam coal, the spacing was increased to 3 in and the depth to 1-1/2 in to provide higher force levels. The flat pick assisted by a 3,000-psi jet indicated negligible force reductions. When cutting with the conical bit, force reductions of 15 pct were observed. The conical bit was far more susceptible to the influence of 3,000-psi water jet than the flat longwall pick. As shown in table 2, the conical bit required twice as much cutting force as the flat pick. Tests in the coalcrete block and Pittsburgh seam coal clearly demonstrated that both materials exhibited negligible cutting force reductions with the 3,000-psi jet assist.

TABLE 2. - Bit cutting force reactions in coalcrete (1-1/2-in penetration and 3-in spacing)

	Conical bit	Flat longwall bit
Cutting force, lbf:		
Dry.................	750	360
With water-jet assist.............	640	370
Force reduction..pct..	15	Neg

Neg Negligible.

The cutting of limestone with the conical bit and 3,000-psi water indicated a 30-pct reduction in normal force and 17-pct reduction in cutting force for a net resultant reduction of 24 pct. This agreed favorably with Ropchan's work.[5] Rock chip distribution studies were conducted on the limestone tests to evaluate cutting efficiency of the conical bit and flat pick. As shown in figure 6, the flat pick produced more larger chips at greater depths of cut than the conical pick and is therefore more efficient. At more shallow depths of cut the conical bit is more efficient.

To verify this observation, cutting forces were compared for dry and water-jet cutting on all of the test materials. It was found that the flat longwall pick used only 40 pct of the cutting force required by the conical bit at the same depth of cut and bit spacing.

Testing with 6,000-psi water-jet assist resulted in substantial force reductions when using the flat and conical picks,

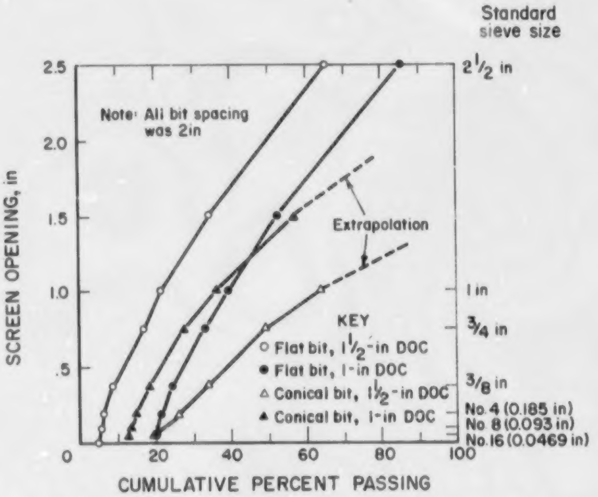

FIGURE 6. - Rock distribution study. (Numbers at right represent standard sieve sizes; DOC = depth of cut.)

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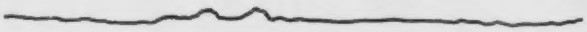
[4] Ropchan, D., F. D. Wang, and J. Wolgamott. Application of Water-Jet-Assisted Drag Bit and Pick Cutter for the Cutting of Coal Measure Rocks (U.S. Dep. Energy contract ET-77-a-01-9082, CO Sch. Mines). Apr. 1980, 120 pp.; NTIS DOE/ET/ 12463-1.

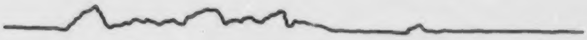
[5] Work cited in footnote 4.

indicating a strong susceptibility to higher jet pressures. In addition, a remarkable decrease in the magnitude and number of peak cutting forces was evident as shown in figures 7 and 8. These figures show typical cuts taken with the In-Seam Tester when cutting the synthetic coal block with the flat and conical pick both dry and with 1,000 and 2,000 psi water-jet assist. The number and magnitude of peak forces were reduced dramatically when using water-jet assist, which makes for a much smoother cutting process that will increase machine reliability and life. These advantages compare favorably with results reported by Ropchan.[6]

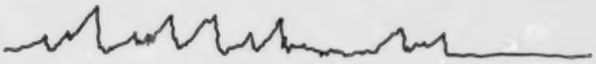


Normal, with 1,000 psi water

Cutting, with 1,000 psi water



Normal, dry

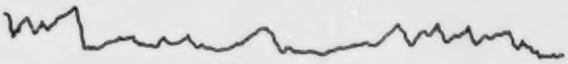


Cutting, dry

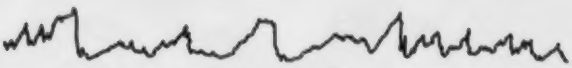
FIGURE 7. - Flat-bit peak cutting forces.

Normal, with 2,000 psi water

Cutting, with 2,000 psi water



Normal, dry



Cutting, dry

FIGURE 8. - Conical-bit peak cutting forces.

Cutting forces were reduced approximately 35 pct when cutting coalcrete using 6,000-psi water-jet assist with a flat bit (fig. 9). The interesting feature of this curve is that the cutting-force reduction decreases as jet pressure is increased beyond 6,000 psi. The plausible reason for this is that at higher jet pressures the jet cuts a slot beyond the depth of the mechanical tool, which decreases the assistance to the chip fragmentation process. More data will be required to adequately explain this phenomenon.

This same phenomenon is also true for the gross force reduction, which is the cumulative effect of the orthogonal cutting forces. As shown in figure 10, the force reduction decreases as jet pressure is increased beyond 6,000 psi. The same reason given above for reductions noted in cutting forces may also be applied here for gross force reductions. Again, more data will be required to explain this phenomenon.

Before a water-jet-assisted rotary cutting system can be employed, a number of problems associated with the use of water jets at 3,000 to 10,000 psi need to be resolved for the equipment to function. These problems include provision for delivering high-pressure water to the rotating drum (cutting head), protection

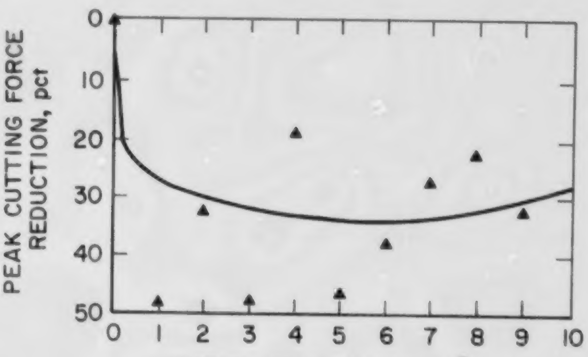


FIGURE 9. - Flat-bit cutting force reduction while cutting coalcrete using 0.6-mm nozzle (correlation coefficient = 0.66).

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[6] Work cited in footnote 4.

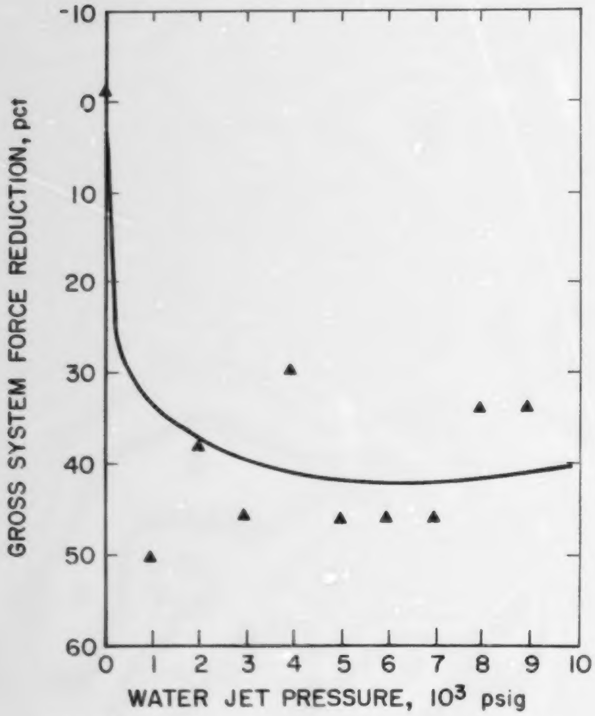

FIGURE 10. - Flat-bit gross system force reduction while cutting coalcrete using 0.6-mm nozzle (correlation coefficient = 0.76).

of the nozzles from rock debris and other possibilities of mechanical damage, a method for quickly and easily replacing nozzles that become worn by erosion, and a system for phasing water-jet activation only when the bit is in contact with the cutting surface. This last provision may be necessary to prevent excessive water usage and to minimize the energy required to operate the jets.

One major aspect of this study was to ensure that the total amount of water added to the cut coal did not exceed what is presently used on continuous miners and coal shearers. As shown in figure 11, the weight of water added to coal is inversely proportional to the machine mining rate. The current upper limit accepted by industry is approximately 1.3 pct water for each ton of mined coal. The water-jet-assisted mining rate reflects the water-jet-induced lower bit forces. However, the water-jet-assisted system does not include a phasing system, which could cut total water usage by a factor of two-thirds. With such a phasing system, the water could be reduced to approximately 0.50 pct per ton of mined coal. This observation was made using the 0.015-in-diam jet nozzle with 6,000 psig and a flow rate of 1.2 gal/min per nozzle.

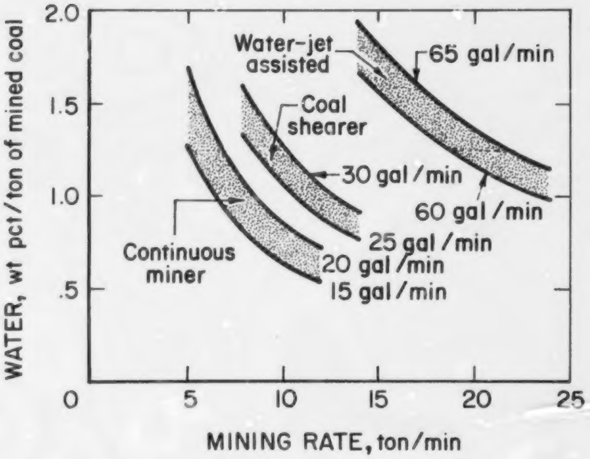

FIGURE 11. - Percent water in cut coal using various mining methods.

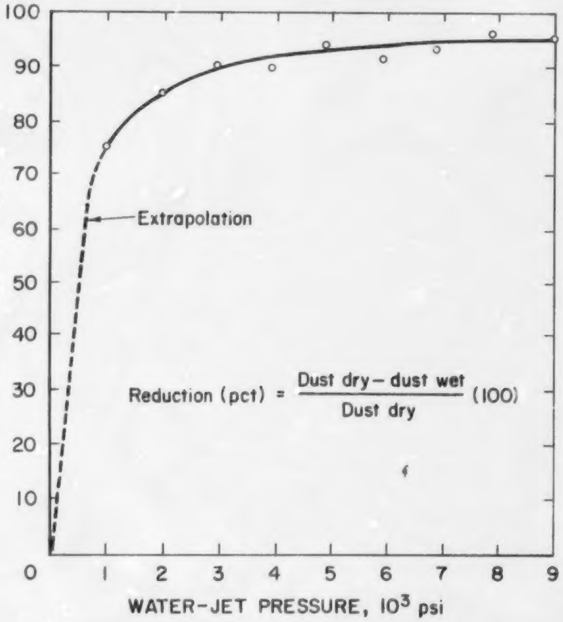

FIGURE 12. - Water-jet-assisted dust reduction potential.

Water-jet-assisted cutting significantly reduces coal dust when cutting the Pittsburgh coal seam underground at the Pittsburgh Research Center (fig. 12). At 4,000 psi, dust reduction was 90 pct when compared to dry cutting. Beyond 4,000 psi no further dust reduction was evident.

CONCLUSION

Four test materials have been evaluated with 3,000-psi water-jet assist. Although effective in coal measure rock, this jet pressure was ineffective in coal and coalcrete. Testing to date indicates that the flat pick is the more efficient cutting tool. Work has commenced using higher pressures. Results indicate that the 6,000-psi water jets will be effective in coal and coalcrete. Though in the early research stage, the water-jet-assisted cutting program, which is being conducted at the Pittsburgh Research Center, has proved encouraging. It does warrant further study.

EXPERIENCE WITH BOOM-TYPE ROADHEADERS EQUIPPED WITH HIGH-PRESSURE WATER-JET SYSTEMS FOR ROADWAY DRIVAGE IN BRITISH COAL MINES

By A. H. Morris[1] and M. G. Tomlin[2]

ABSTRACT

In 1978, collaboration was established between the Bureau of Mines and the National Coal Board (United Kingdom) (NCB) on a project to develop and test a high-pressure water-jet system fitted to a boom-type roadheader. Earlier laboratory trials had indicated that such a system could significantly improve the cutting performance of a roadheader and that other benefits in terms of extended pick life, better dust suppression and reduced frictional sparking would also be achieved.

Surface trials with a prototype system showed that the expected benefits could be realized, and further equipment development was then carried out so that the potential of the technique could be assessed when applied in production situations.

Four production-type water-jet systems, each incorporating different features as regards pump units, seals, nozzles, etc., have been produced and fitted to roadheaders. The first of these has successfully completed an underground trial, and trials with the others are proceeding. The experience gained with these machines, the performance of the water-jet systems, and their effect on operation are discussed.

INTRODUCTION

Operating trials with a boom-type roadheader equipped with the National Coal Board prototype high-pressure water-jet system were carried out at Middleton Limestone Mine in 1981.[3] Figure 1 shows the system in operation. During these trials, the technique showed good potential for improving the roadheader cutting performance. It was agreed that the development of preproduction versions should proceed, so that full-scale underground trials could take place. Two machines would be produced by Anderson Strathclyde and Dosco, respectively, using technical information and trial results provided by NCB's Mines Research and Development Establishment (MRDE); two others would be Dosco Mk.IIA machines modified by MRDE.

ACKNOWLEDGMENT

The authors thank the Director of Mining Research and Development, National Coal Board, for permission to publish this paper. The views expressed are their own and not necessarily those of the NCB.

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[1] Chief project manager.

[2] Project engineer.

Mines Research and Development Establishment, Tunneling and Transport Branch, National Coal Board, Bretby, United Kingdom.

[3] Plumpton, N. A., and M. G. Tomlin. The Development of a Water Jet System To Improve the Performance of a Boom Type Roadheader. Paper in 6th International Symposium on Jet Cutting Technology (Univ. Surrey, United Kingdom, Apr. 6-8, 1982). BHRA Fluid Engineering, Cransfield, Bedford, United Kingdom, 1982, pp. 267-282.

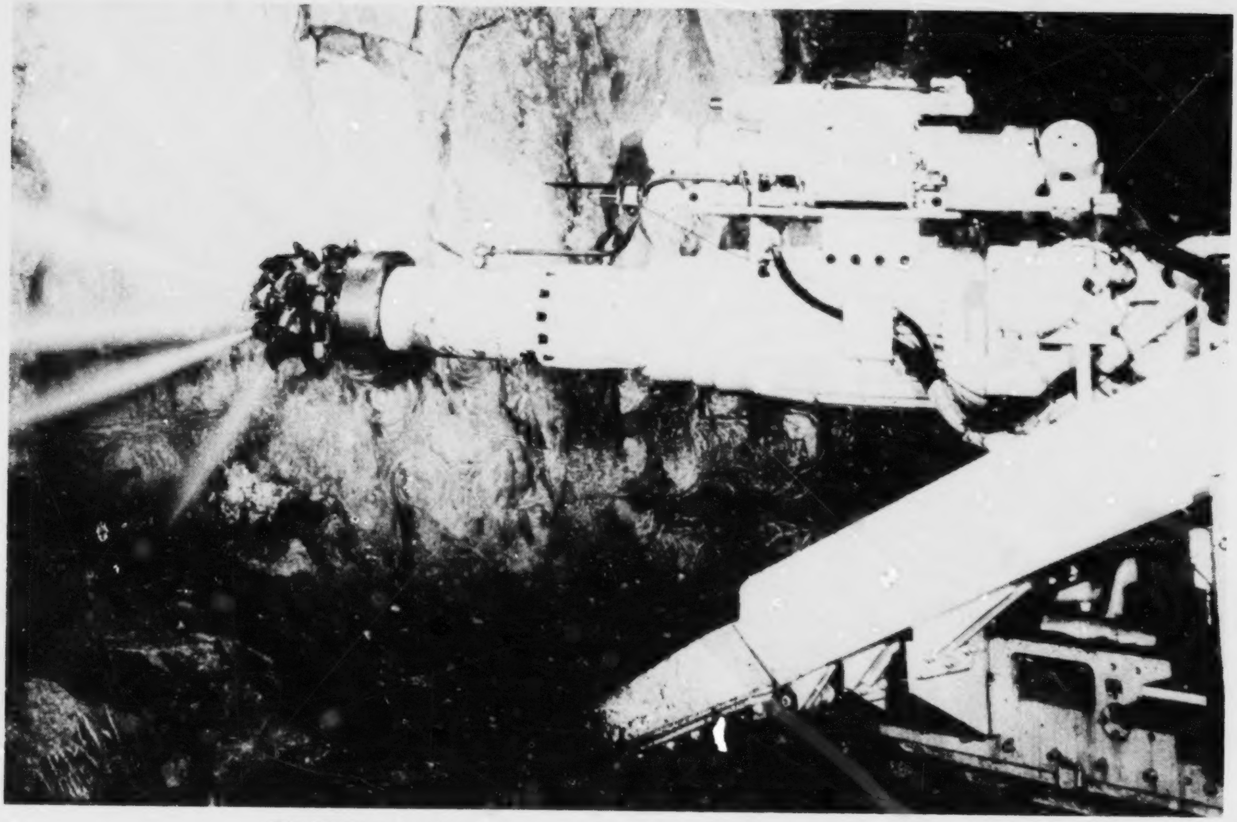

FIGURE 1. - NCB prototype high-pressure water-jet system.

DEVELOPMENT OF PREPRODUCTION VERSION

GENERAL

The high-pressure water-jet system operates at a maximum water pressure of 10,000 psi. It comprises a high-pressure water pump and a rotary seal unit to introduce the water into the roadheader drive shaft and cutting head, the cutting head being equipped with nozzles to direct high-pressure jets into the area of the cutting picks. Operational experience with the prototype system indicated that considerable further development of the rotary seal was necessary if an acceptable life expectancy were to be achieved in a production environment and that there was scope for improvement in nozzle design to produce more efficient jets. The original roadheader equipped with the prototype system was retained at the limestone mine to gain further operational experience and for use as a test bed for new seal and nozzle developments.

ROTARY SEAL DEVELOPMENT

Development of the high-pressure water seal for the prototype system had been concentrated on the requirement to fit such a seal around the cutting head shaft as shown in figure 2. Further development based on this configuration resulted in an increase in seal life from 50 to

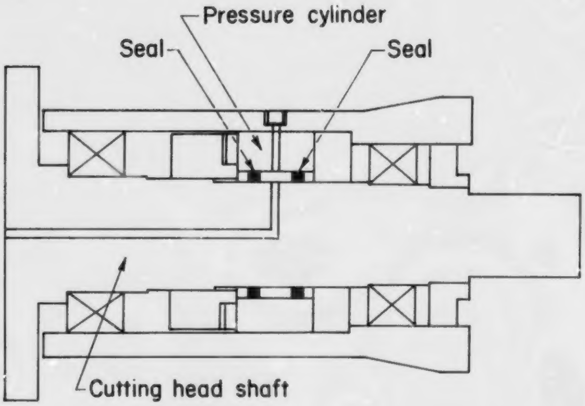
Pressure cylinder
Seal
Seal
Cutting head shaft

FIGURE 2. - Rotary seal assembly.

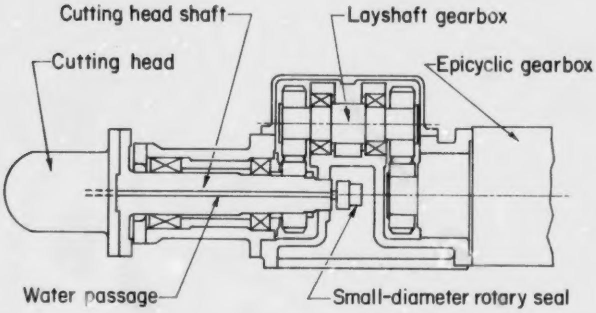
Cutting head shaft
Layshaft gearbox
Cutting head
Epicyclic gearbox
Water passage
Small-diameter rotary seal

FIGURE 3. - Section through layshaft gearbox.

140 h, though this was unpredictable and still far short of the minimum acceptable life of about 500 h. A seal change was also a major operation, and machine downtime was excessive. Because of these factors, development was switched to two alternative approaches. Both incorporate a small-diameter seal built into a cartridge assembly, which is readily accessible and can be easily and quickly changed, thus reducing the importance of seal life as a limiting factor; also it was expected that seal life would dramatically improve as the diameter decreased.

The first approach was to introduce a layshaft gearbox into the roadheader boom prior to the cutting head shaft (fig. 3). A gearbox was designed and manufactured (fig. 4) and extensively tested on the roadheader. It proved completely reliable in operation, and the seal unit could be changed in a few minutes. The small-diameter seal unit developed concurrently for this application also proved successful, and seal lives in excess of 200 h were achieved.

The second alternative is shown in figure 5. The roadheader boom has been modified to accommodate an axial water passage along its full length, with the

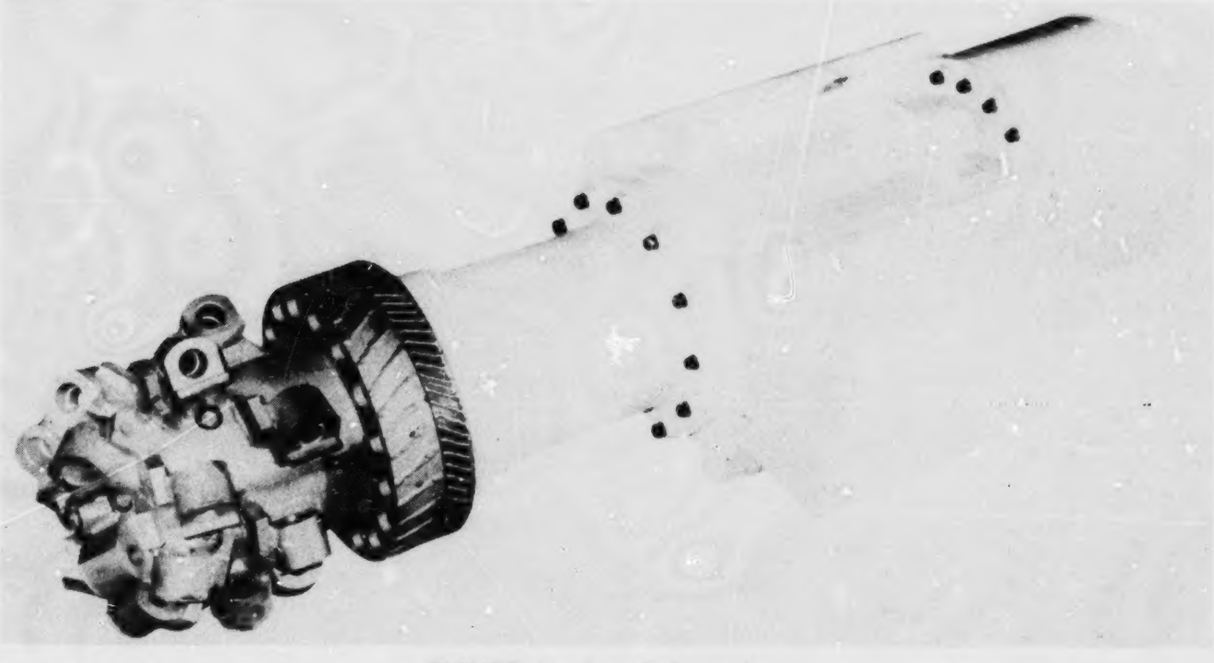

FIGURE 4. - Layshaft gearbox.

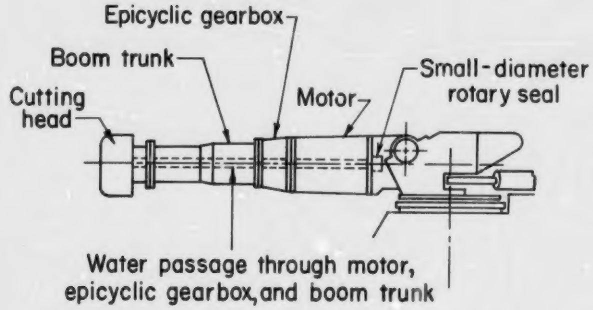
Epicyclic gearbox
Boom trunk
Cutting head
Motor
Small-diameter rotary seal
Water passage through motor, epicyclic gearbox, and boom trunk

FIGURE 5. - Boom with axial water passage.

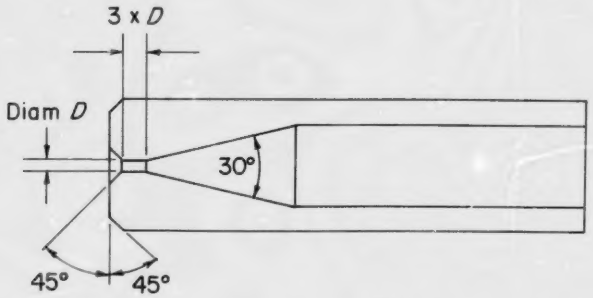

FIGURE 6. - Tungsten carbide nozzle.

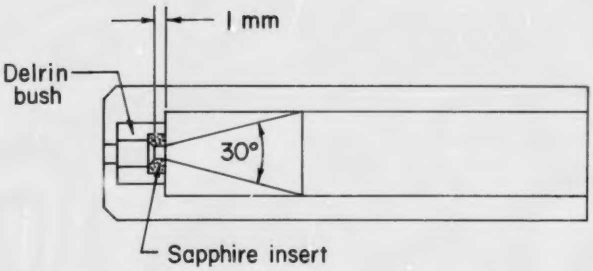

FIGURE 7. - Synthetic sapphire nozzle.

small-diameter seal unit mounted at the end remote from the cutting head. While time restrictions prevented this method being tested in situ, it was felt that it had every chance of success.

Both methods have been adopted in the preproduction systems described later.

NOZZLE DEVELOPMENT

A test program was initiated to assess the comparative performance of various nozzle types against that of the simple, synthetic sapphire orifices used on the prototype system. Nozzle performance was recorded on a test rig by measuring the pressure profile across the jet stream at various distances from the nozzle.

The type of nozzle which gave best results is shown in figure 6. Manufactured from tungsten carbide, this type has a highly polished inner face with a surface finish of 0.15 µm. Nozzles of similar shape, but made from stainless steel and with an inset synthetic sapphire orifice, as shown in figure 7, also gave good results, although slightly inferior to the tungsten carbide type.

Nozzle life and efficiency ratings could not be established during the testing period, and it was decided that both types should be incorporated in the preproduction versions. This would allow assessment of the useful life of each type by regularly checking the performance of sample nozzles on the test rig and recording any fall off in efficency over long periods.

DESCRIPTION OF PREPRODUCTION SYSTEMS

NCB PREPRODUCTION VERSION TYPE 1

The type 1 system closely resembles the prototype system used at Middleton Limestone Mine, with some refinements based on test results and further development work.

The base machine is a Dosco Mk.IIA roadheader as shown in figure 8. High-pressure water is generated by an oil-water intensifier mounted on the roadheader boom. Maximum output from the intensifier is 45 L/min at 10,000 psi pressure, and it is powered by a hydraulic swashplate pump unit at the rear of the machine. This pump unit is fitted with a remote control system to allow the machine operator to select either high-pressure water output from the intensifier or low-pressure output for dust suppression purposes if high-pressure jet assistance is not required.

A layshaft gearbox with small-diameter seal unit is fitted into the boom to accept the water output from the intensifier. The cutting head is equipped with

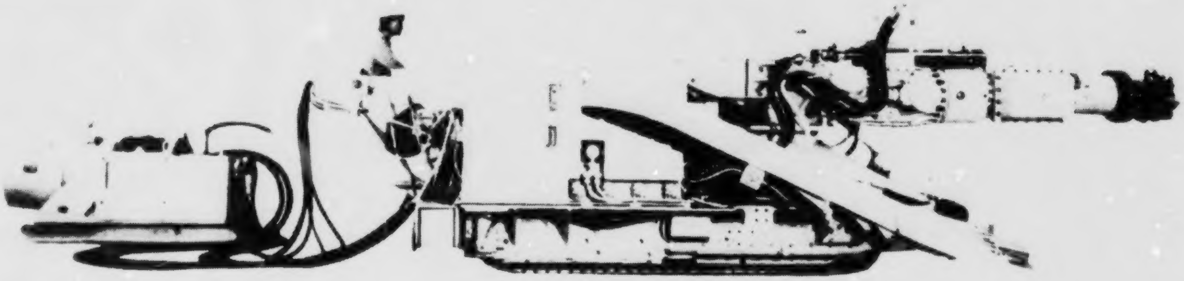

FIGURE 8. - NCB preproduction version, type 1.

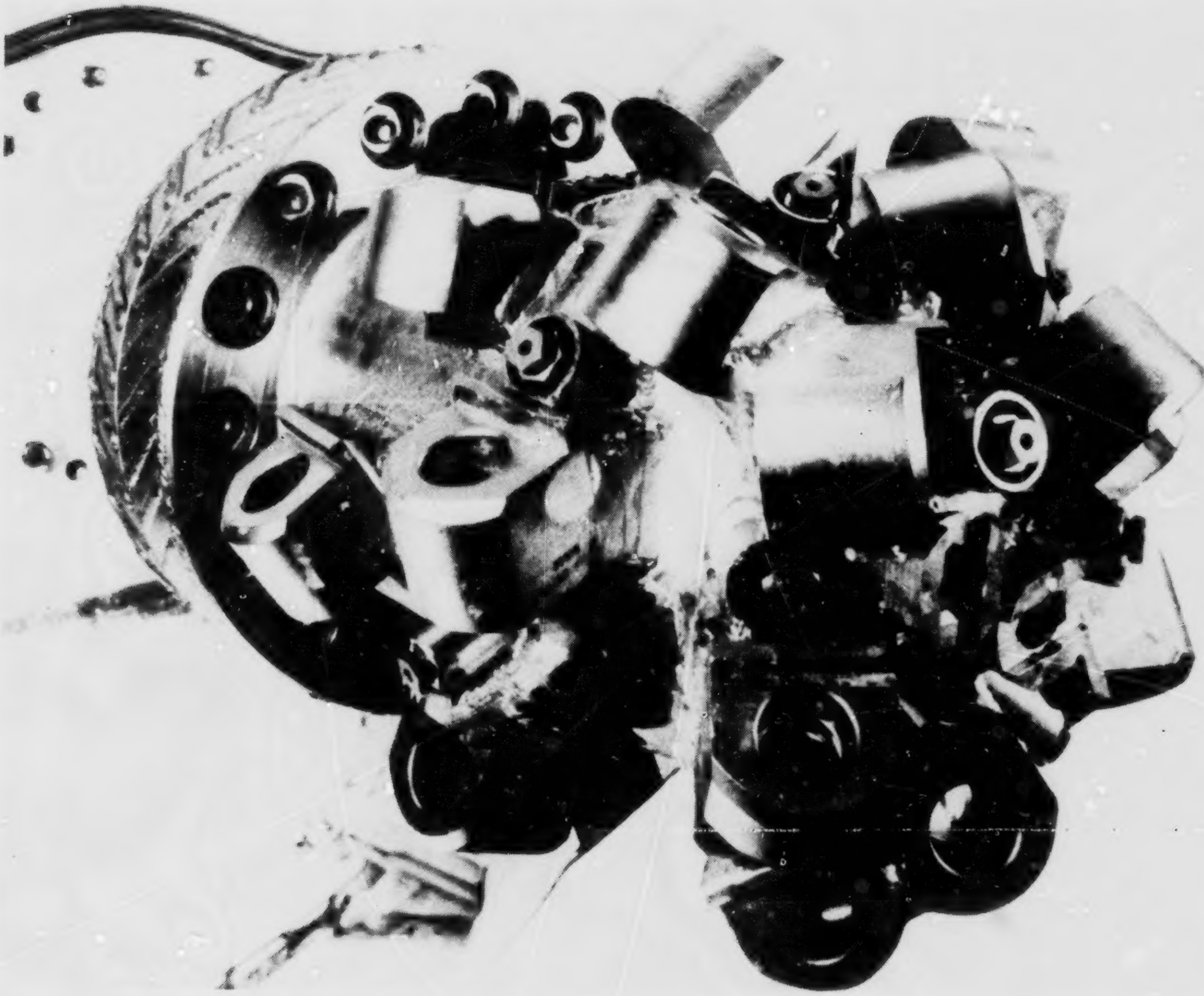

FIGURE 9. - Cutting head.

tungsten carbide nozzles. These stand clear of the cutting head body to minimize the standoff distance from nozzle to pick tip and are protected from external damage by steel shrouds, as shown in figure 9.

The water-jet system is interlocked with the roadheader electrical and hydraulic circuits for "operator" protection. Prestart warning is given by low-pressure drenching sprays directed at the cutting head, while the high-pressure jets cannot be switched on unless the cutting head is running.

NCB PREPRODUCTION VERSION TYPE 2

The type 2 preproduction version is shown in figure 10. The only difference between the type 2 and type 1 systems is that, for the type 2, the single intensifier mounted on the roadheader boom has been replaced by two smaller intensifiers of equivalent capacity. These are mounted on each side of the boom, as shown in figure 11, to improve the machine operator's view of the cutting head.

DOSCO PREPRODUCTION SYSTEM

The Dosco system is again based on a Dosco MK.IIA roadheader, which has been modified to accommodate the high-pressure water pump on the machine base (fig. 12). Some machine components have been interchanged, to enable a 150-kW through-shaft motor to be mounted at the side of the machine. This motor is then used to drive both the roadheader hydraulic pump and the high-pressure water pump. The pump used is a diaphragm-type, fixed-displacement unit with a maximum output of 45 L/min at 10,000-psi pressure. A water header tank is mounted above the pump, and the hydraulic circuit is arranged so that surplus output can be dumped back to this tank when high-pressure water is not required.

A layshaft gearbox with small-diameter seal is fitted into the boom, as on the NCB systems, and high-pressure water is fed to this via a rigid steel pipe system; horizontal and vertical articulated joints accommodate movement of the roadheader boom. The cutting head is similar in design to those used on the NCB systems, except that it is equipped with synthetic sapphire nozzles.

ANDERSON STRATHCLYDE PREPRODUCTION SYSTEM

This system has been installed on an Anderson Strathclyde RH22 roadheader and is shown in figure 13. A triplex-piston type high-pressure water pump and water header tank are mounted on the rear of the machine behind the driver's position. This pump has a higher capacity--68 L/min at 10,000-psi pressure--than the three systems previously described.

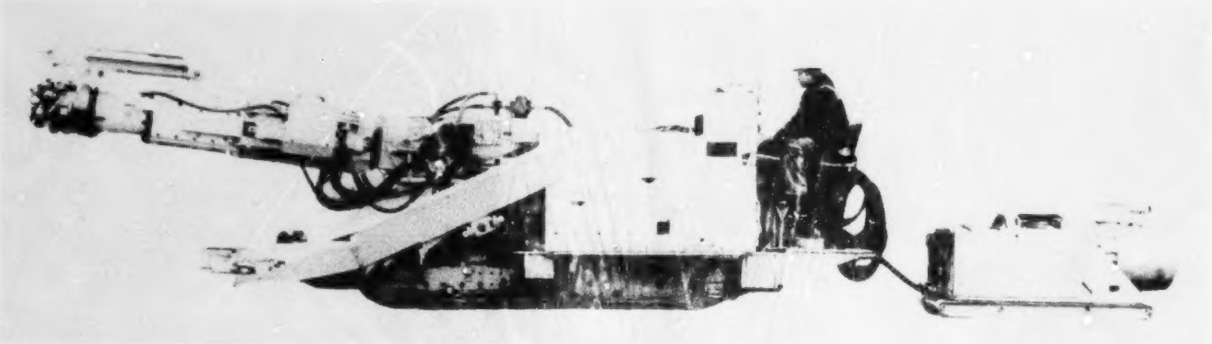

FIGURE 10. - NCB preproduction version, type 2.

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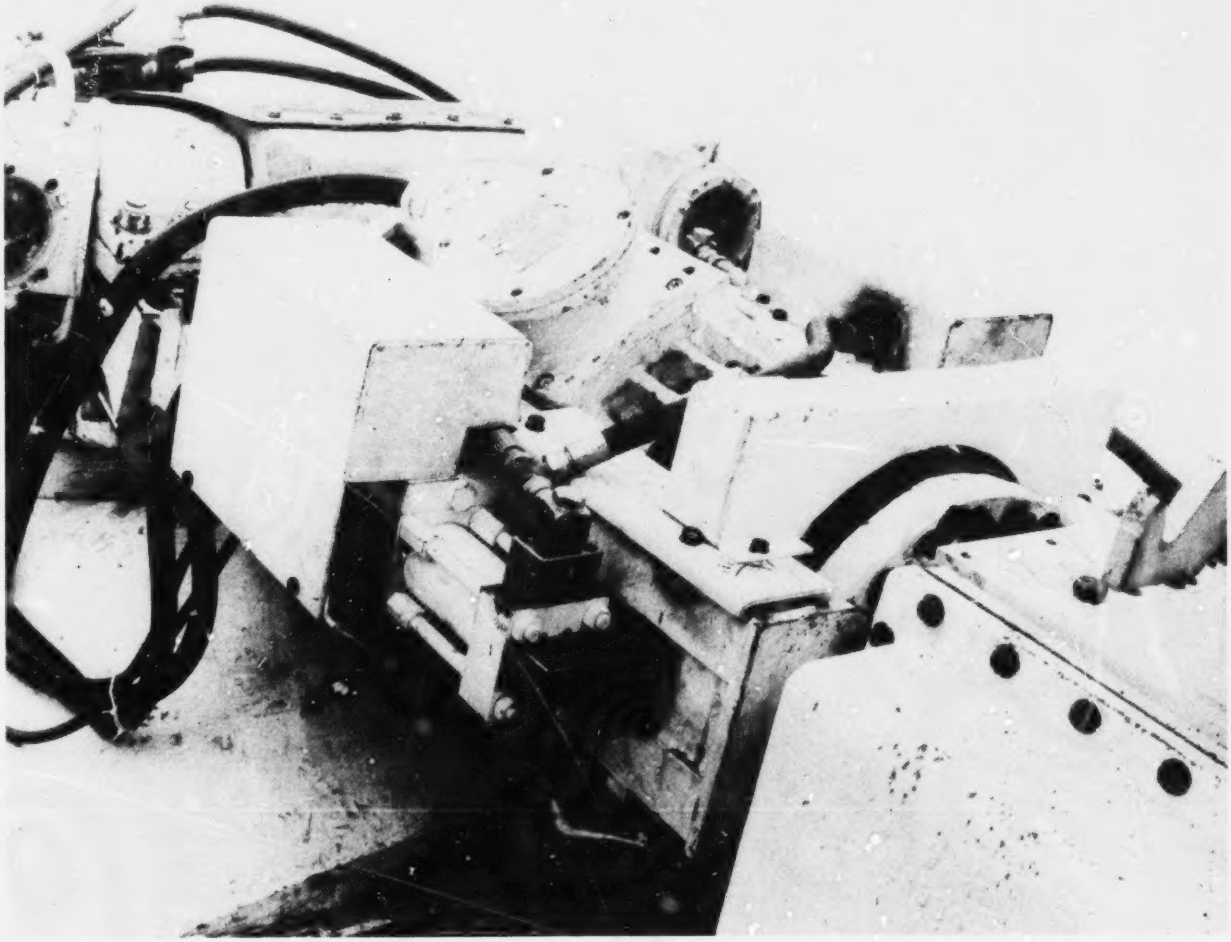

FIGURE 11. - Twin intensifiers mounted on boom.

The roadheader is equipped with a boom incorporating an axial water passage and has a small-diameter rotary seal mounted at the motor end. The boom has a telescopic facility, and a sliding seal arrangement is incorporated in the water passage at the cutting head end. High-pressure water is fed to the boom by means of a flexible hose which, for reasons of safety, is shrouded by another heavy-duty hydraulic hose. The cutting head is based on the normal design used on the RH22 roadheader and has provision for high-pressure nozzles to be fitted in front of all 24 picks. As on the two NCB systems, the nozzles used are tungsten carbide.

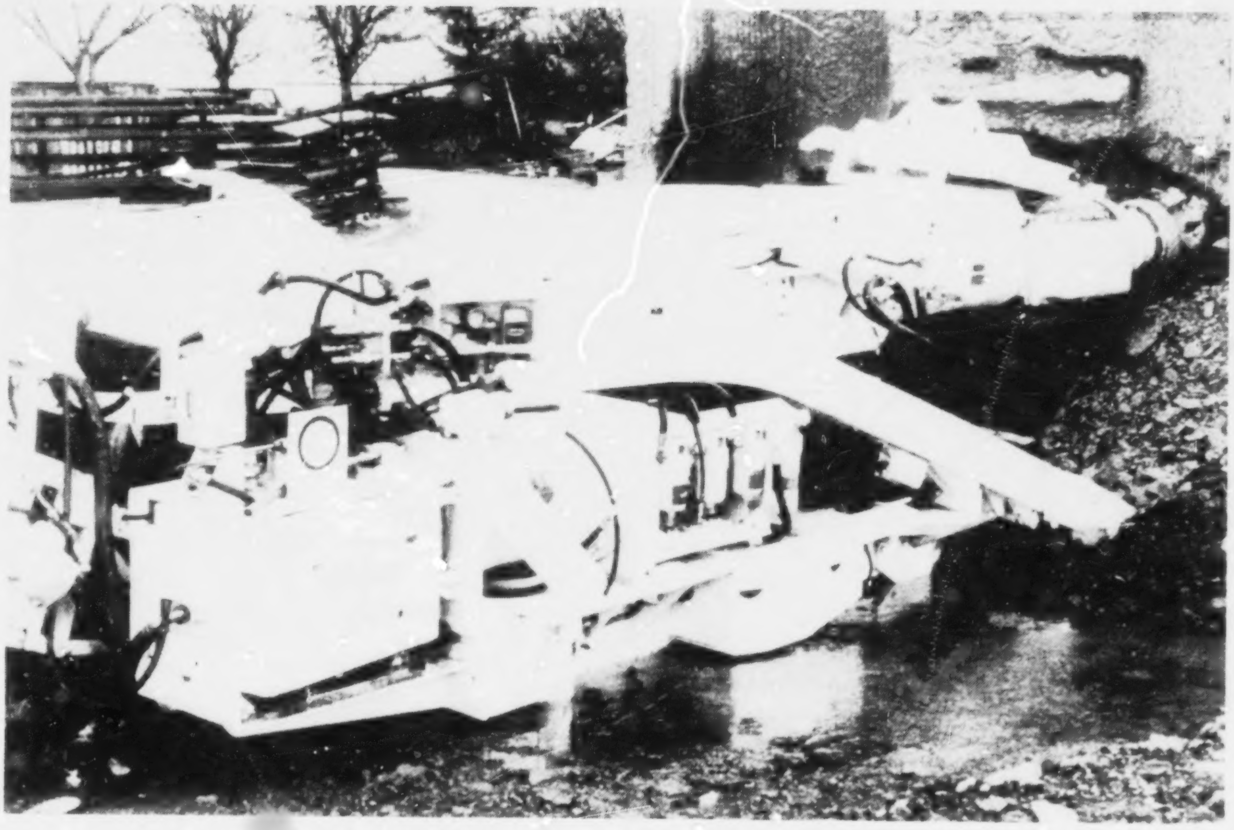

FIGURE 12. - Dosco preproduction system.

UNDERGROUND TRIALS

GENERAL

At the time of writing, the two NCB systems and the Dosco system had been commissioned and deployed to collieries, but trials had not yet commenced. Comments, therefore, are restricted to the performance of the Anderson Strathclyde roadheader, which has been in operation at Sutton Manor Colliery since August 1983.

Before taking the roadheader underground, operator training was carried out on the surface by MRDE and Anderson Strathclyde. Colliery staff were made familiar with the high-pressure equipment and its operation and were made aware of the hazards involved if the equipment was misused or if the rules established for safe operation were broken.

The roadheader is being used to drive a main access roadway to coal reserves in the High Florida Seam. The roadway passes through a wide variety of strata, ranging from soft mudstones to hard siltstones and sandstones with some ironstone bands and inclusions. So far, approximately 150 m of drivage has been completed with good results; the water-jet system is in continuous use and has been readily accepted by the heading teams. Colliery staff are satisfied that it is contributing significantly to the overall performance of the roadheader.

CUTTING PERFORMANCE

The comparative cutting performance of the roadheader with and without high-pressure jet assistance is being

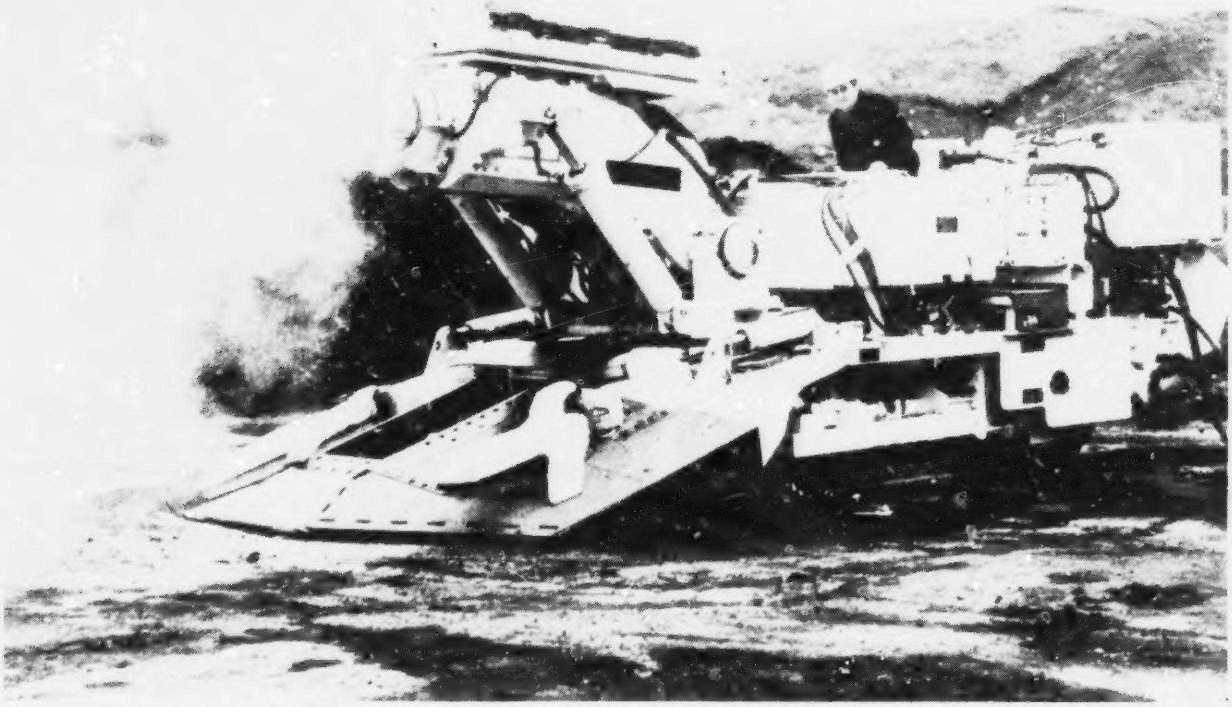

FIGURE 13. - Anderson Strathclyde preproduction system.

monitored in different strata as the roadway advances. The results of the tests completed to date are summarized in table 1. Increases in cutting rate and reductions in specific energy requirements have been recorded in all cases, although there is considerable variation for each rock type. Examination of the recorder traces of the cutting head power consumption during tests also indicates a marked reduction in vibration when jet assistance is used. This was also visually evident. Again, the effect has varied in the different rock types, but was extremely significant in some cases. as illustrated in figure 14.

TABLE 1. - Comparative cutting performance with and without high-pressure jet assistance

Test	Rock type	Strength, psi		Cutting rate, ton/h		Specific energy requirement, $m^3/(kW \cdot h)$	
		Compressive	Tensile	With	Without	With	Without
1	Mudstone..................	8,400	2,200	16.8	15.2	2.20	3.58
2	...do.....................	6,300	2,100	17.1	11.1	2.23	3.32
3	Silty sandstone...........	11,800	3,000	2.8	2.5	9.00	10.27
4	Siltstone and/or sandstone	10,200	2,700	7.8	2.8	2.87	8.90
5	Siltstone.................	5,900	1,700	10.1	8.1	3.32	4.09
6	Mudstone..................	5,900	1,900	37.4	18.4	1.21	2.46
7	...do.....................	6,500	1,700	16.2	13.0	1.65	2.30

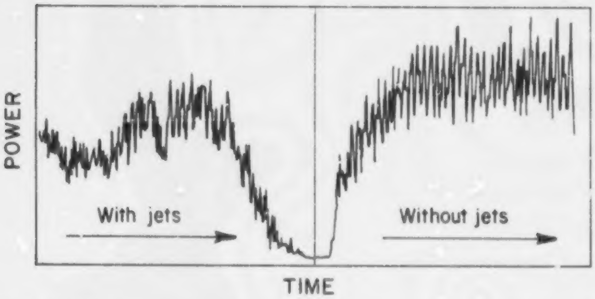

FIGURE 14. - Cutting head power versus time trace.

DUST SUPPRESSION

From the onset of the trial it was obvious that dust suppression with high-pressure jets was far superior to that achieved with conventional low-pressure (300-psi) sprays. This, in fact, has caused problems when monitoring the machine cutting performance, since the operators are extremely reluctant to operate without jet assistance even for short test periods. Continuous monitoring of respirable dust levels in the roadway over full working shift periods has shown that levels below 2 mg/m^3 have been consistently maintained, even though forcing ventilation is used. This is well below the maximum acceptable level of 5 mg/m^3.

The results of an individual series of tests carried out to establish the respirable dust make during the cutting cycle are given in figure 15. These tests were carried out consecutively in the same band of strata, and, by fitting suitably sized nozzles for each test the water flow of 68 L/min was kept constant over a range of pressures from 300 to 10,000 psi. The benefits, in terms of dust reduction, of increasing the water pressure are apparent.

PICK LIFE

Pick consumption on the length of drivage already completed has averaged 0.7 per meter of advance. Since jet assistance has been used continuously, no comparison can be made with pick consumption when jet assistance is not used. However, one short test has been carried out, and this indicates that considerable increase in pick life is being achieved.

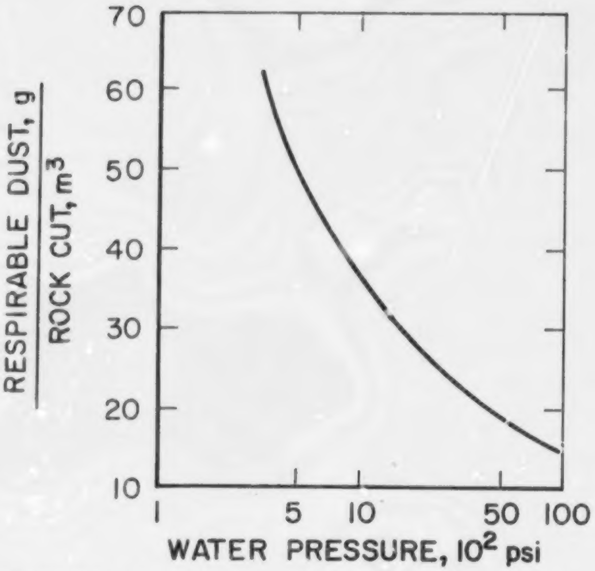

FIGURE 15. - Results of dust suppression tests.

For the purposes of this test, two nozzles were blanked off, one adjacent to a pick near the front of the cutting head and the other adjacent to a pick at the rear of the cutting head. During 1 m of advance, the front pick needed to be changed three times and the rear pick twice. Only 1 of the other 22 picks on the head failed during the same period. It was hoped that this test could be repeated over a longer period so that accurate comparisons could be established; however, occasional sparking was noted during the test from the two picks without jets, and, in view of the gaseous conditions prevailing in the roadway, the test was not repeated.

EQUIPMENT PERFORMANCE

The high-pressure water system has operated well, and the only problems encountered have been with the sliding seal in the telescopic boom. This has failed on three occasions but has since been redesigned and is now proving reliable in operation.

Expected problems due to nozzle blockages and water accumulation on the roadway floor (based on operational experience with the prototype system) have not been as severe as expected.

The water feed to the high-pressure pump is filtered at 10 μm through a bank of filters of diminishing size; normally, only one or two nozzles become blocked during a working week. Blockages can easily be cleared using a twist drill of the same diameter as the nozzle orifice.

The floor of the roadway has remained generally dry, although some pools of water have accumulated in the working area. These do not affect maneuverability of the roadheader, though some problems have occurred with the loading-out conveyors due to slurry causing blockages. A pump has been installed in the roadway to clear the water if it becomes excessive.

CONCLUSIONS

Current trials with the water-jet system at Sutton Manor have proved that, to some degree, all the benefits expected from use of the technique, as evidenced by the first trials at Middleton, can be achieved.

Cutting rates have been measurably improved, and the forces on the cutting picks have been reduced, as indicated by the lower specific energy requirement at the cutting head.

The effect of high-pressure jets in reducing dust make has been remarkable, and this may well be a major factor in influencing further exploitation of the system, especially when considered in conjunction with the observed elimination of frictional sparking.

Apart from early problems with the faulty sliding seal (which have since been solved), the high-pressure equipment has so far proved reliable in operation.

What is also important is the way in which this new technology has been readily accepted by the colliery staff. Pretrial training has obviously paid dividends in that the confidence of the colliery staff has been gained; this exercise is currently being repeated at the other three trial sites.

It would be premature to forecast the extent of future exploitation of high-pressure water-jet assistance, operational experience having not yet been gained with the other three systems. These will be operating in different conditions, a fact that may well highlight problems not apparent from the Sutton Manor trial. Trials with the NCB type 1 and Dosco systems are now imminent, while trials with the NCB type 2 system will follow shortly thereafter. When these trials are well advanced, the overall performance of all four systems will be assessed. Only then will any commitment on further exploitation be made.

DEVELOPMENT WORK FOR COAL WINNING TECHNOLOGY

By Dr. E. H. Henkel[1]

INTRODUCTION

Worldwide, shearer-loaders and coal ploughs are the predominant machine designs for coal winning on longwall faces. Even though these systems are capable of high production performance under optimized operating conditions, they do not comply fully with tomorrow's expectations, which may be summarized as follows:

1. Coal winning, including high performance, optimized web, and use on face ends.
2. Adaptability to geological conditions, including seam thickness, strength of coal and adjacent strata, and working through faults.
3. Working conditions including low-dust operation, improved mine climate, and higher safety standards.
4. Economic aspects and cost reduction, including coal preparation (larger particle size, less fines, and reduced humidity), production (better use of energy, higher reliability, and wider application range), and organization (systematic monitoring and maintenance).

With consideration of these requirements, the present limits of practicality for both types of coal winning systems are set as shown on figure 1. Independent of strength criteria, the application range for conveyor-mounted shearer loaders is in seam thicknesses of more than 1.8 m. For seam thicknesses of less than 1.8 m, in-web shearers may be used. Under the conditions prevailing in German coal mining, however, the performance of in-web shearers is unsatisfactory.

The main application range of the coal plough is found in the lower seam thicknesses; however, coal plough operations are limited to ploughable seams. Therefore, seams of hard coal and those within hard adjacent strata constitute a range for which, up to the present, cost-effective coal winning equipment for longwall faces has been nonexistent worldwide.

These limits of practicality for shearer-loader and coal plough operations show that more concentrated energy transmission by the coal winning tools is required for recovery of hard coal, selective mining of rock, arriving at large webs, obtaining a better particle size, and eventually reducing the dust release.

With respect to fulfillment of the above-specified requirements, the research for new technologies resulted in three candidate systems for coal winning:

1. Use of high-pressure water jets.
2. Use of hydraulic impact devices.
3. Vibration transmission for fracturing the mineral.

This paper discusses all three techniques, with special emphasis on the use of high-pressure water jets.

ACKNOWLEDGMENTS

The research and development work was sponsored by the Bundesminister fur Forschung und Technologie (Federal Ministry for Research and Technology) as well as by the Minister fur Wirtschaft, Mittelstand und Verkehr (Ministry for Economics and Transport) of Northrhine-Westfalia. The project was set up jointly by M.A.N.-GHH Sterkrade, Klockner-Becorit GmbH, Ruhrkohle AG, and Bergbau-Forschung GmbH.

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[1] Head of Department and Test Side Coal Winning, Conveying, Face End Systems, Bergbau-Forschung GmbH, Essen, Federal Republic of Germany.

GENERAL TESTING PROCEDURES

For cost reasons, the development and testing of mining machinery is necessarily done in testing installations on the surface. However, one of the problems of surface testing is realistic simulation of operating conditions. This is accomplished with a simulated coal block that approximates the strength and rupture behavior in terms of required cutting forces. The volume of the mineral cut must also be comparable to that of the mineral encountered in actual mining operations. Since these problems have been dealt with in the literature, I prefer just to give a concise report on our experience.

For industrial-scale tests, blends of marl, cement, and water are cast to obtain simulated coal. The setting time of these blends is approximately 3 months. Good results have been obtained varying the components to obtain degrees of hardness. However, the requirement for more and more mockup coal faces necessitated shorter setting times, requiring simultaneous maintenance of controlled strength properties. Accordingly, additives were proportioned to these blends, and these additives lead to shorter setting periods as a result of a lower water proportion of the blend. Nevertheless, the problem of determining cutting forces, versus the volume of cutoff mineral, remained the same. The ratio cannot be established by determining compressive and tensile strength run on sample cubes of the same blend. For comparative assessment of cuttability of simulated coal face material and natural coal with dirt bands, we developed a cuttability tester which measures cutting force and feed thrust. In this way a comparison of operating conditions can be made. However, the simulation of in situ rock pressures cannot be accomplished. Using the cuttability tester to assess a coal winning method for use in a particular seam was practiced in approximately 50 cases in the Ruhr district.

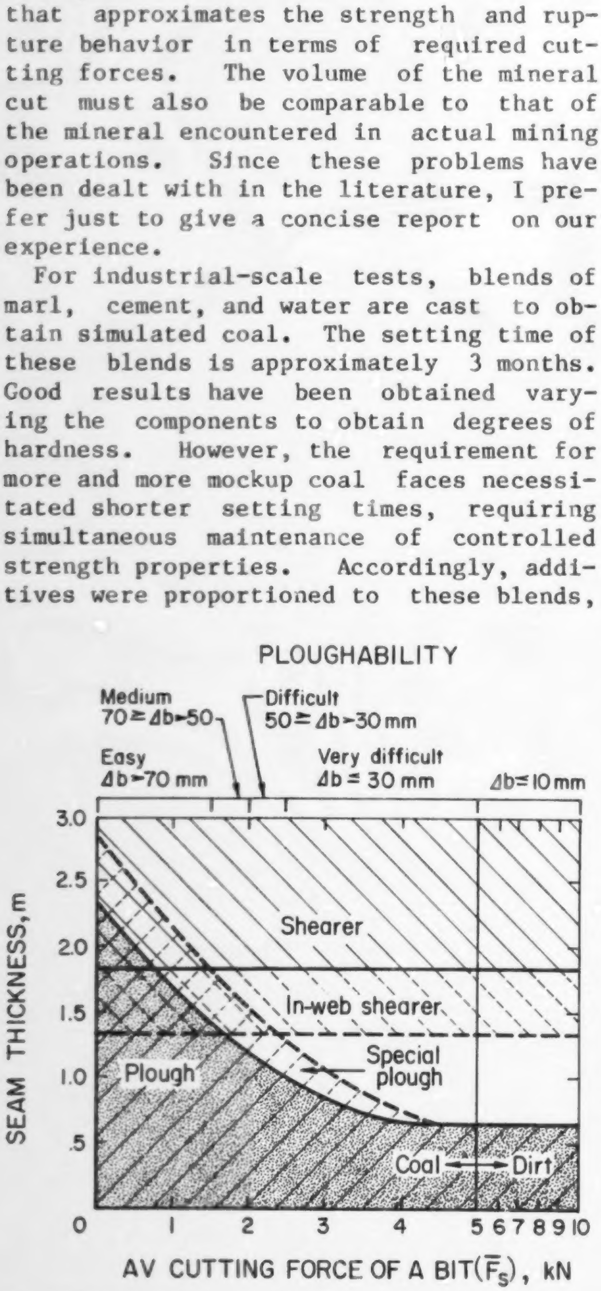

FIGURE 1. - Applications of coal winning machines.

The following are remarks regarding procedures followed in machine development on the testing premises of Bergbau-Forschung GmbH. Basically the work was performed in three phases.

PHASE 1: TECHNICAL SCALE BASIC RESEARCH ON A NEW CUTTING TECHNIQUE

Experimental investigations to assess the efficiency of any new cutting technology and optimize parameters are run almost entirely by Bergbau-Forschung. In this phase, theoretical investigations carried out are of only a complementary character. If promising results are obtained, the second development phase is initiated.

PHASE 2: CONSTRUCTION AND TESTING OF EXPERIMENTAL UNITS

Application of a new technique means testing on the surface and underground. Accordingly, experimental units are fabricated with commercially available machine elements and equipment. To allow assessment of coal winning capacity, the experimental units correspond as far as possible with a later prototype in terms of designed layout, drive rating, and traveling speed. In this development phase, a manufacturer is sought who is interested in the new technique and who cooperates in setting up the experimental unit. Now the sometimes very long period of testing and modification on surface test rigs begins. If the results are positive, a colliery is located where the experimental unit can be tested underground. If possible, to allow ample opportunity for evaluation and modification, all underground testing should be conducted on nonproduction faces. If good results in terms of performance, reliability, and maneuverability in underground operations are obtained, then the third phase, construction of the prototype, is begun.

PHASE 3: CONSTRUCTION AND TESTING OF THE PROTOTYPE

Construction and, above all, testing of the prototype necessarily require cooperation of engineers from the manufacturer, the colliery, and the research center. Only this cooperation enables a maximum of technology transfer to take place, and only in this way is it assured that the participating engineers become personally involved in the project. Without these people participating, the success of machine development becomes rather questionable.

The new machine is designed, fabricated, and tested on the surface according to design parameters developed from experimental units. Later success in underground operations is to a considerable extent a function of the testing conditions on the surface, i.e., the quality of definition and simulation of the geological features and operating conditions.

WATER-JET CUTTING TECHNOLOGY: STATE OF DEVELOPMENT

During the recent past, several reports have been written about using high-pressure water jets for coal winning. The course of development leading up to the present is as follows:

OPTIMIZATION OF CUTTING HEADS

In the course of the basic investigations, the cutting parameters of the water-jet technology were investigated for fixed and oscillating nozzles (fig. 2). The tests were run on a special test rig with "normally ploughable" mockup coal. For measuring the cutting forces, the cutting head was mounted in a special frame for triaxial measurements. For a pressure of 10,000 psi at the pump and a flow of 150 L/min, the following optimized cutting parameters were obtained:

Nozzle diameter (d)......	mm..	1.65-1.95
Oscillating frequency (f)	Hz..	3-5
Depth of cut (b).........	mm..	220
Tractive effort on the plough chain (F)........	kN..	40

Compared to mechanical ploughing the combined hard metal-jet cutting technique resulted in an increase of cutting depths of almost 100 pct at identical tractive effort on the chain (fig. 3). These results were obtained for the range of coal defined as "normally ploughable."

CONSTRUCTION OF AN EXPERIMENTAL UNIT

For testing the cutting technology, an experimental unit was made up from existing machinery components, namely, coal plough, guides and skids, 300-kW drum-shearer loader motor, two high-pressure pumps, and four cutting heads on each machine side. One cutting head is arranged for horizontally cutting the floor. The experimental unit was pulled by an hydrostatic motor at speeds adjustable between 0.1 and 0.4 m/s (fig. 4)

Subsequent to the tests on the mockup coalface, operation tests underground were run at the Lohberg colliery. The experimental face was worked at a thickness of M = 1.8 m and a length of L = 50 m. The coal strength may be categorized as "normally ploughable."

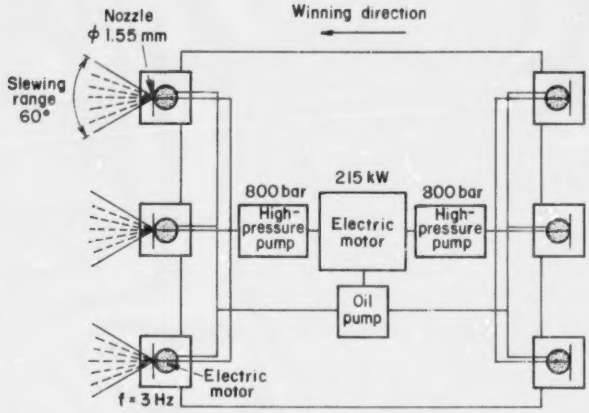

FIGURE 2. - Jet miner, principle diagram.

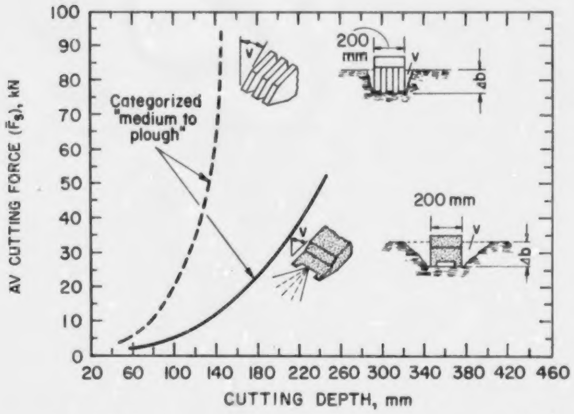

FIGURE 3. - Comparison of mechanical cutting and jet cutting.

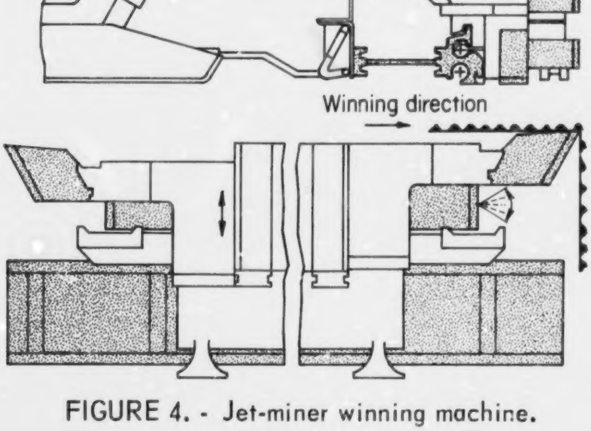

FIGURE 4. - Jet-miner winning machine.

The experimental operation yielded the following results:

- The coal face was undercut smoothly by the oscillating high-pressure water jets and subsequently broken off by the hard-metal tools.

- The cutting heads exhibited no wear, and in particular, no wear attributable to mechanical cutting work.

- The measured chain force, F = 340 kN, shows that the power requirement of the high-pressure pumps could be reduced from P = 300 kW to P = 220 kW, and that the water flow could be reduced from 226 L/min to 170 L/min.

- At a depth of cut of b = 400 mm, a traveling speed of v = 0.4 m/s was obtained.

- The raw coal exhibited an excellent particle size distribution.

- The quantity of dust released corresponded to approximately 30 pct of the dust produced by a shearer operating in the same seam.

DEVELOPMENT OF THE JET-MINER CONCEPT

After successful trials run with the experimental version, the development of the first Jet-Miner prototype was started in cooperation with Ruhrkohle AG, M.A.N.-GHH-Sterkrade, and Bergbau-Forschung GmbH. Since the basic suitability of the oscillating-water-jet system was proved throughout the trials, the original concept and design features of the cutting heads were retained. As mentioned in the introduction, the Jet-Miner was supposed to be used in seam thicknesses of 1.0 to 1.5 m. Accordingly, a machine body of 1,000 mm height was designed. An array of two or three cutting heads ranging in height from 1.0 to 1.5 m was designed for the machine.

During the underground trials, clearing problems arose, resulting in the total machine body of the Jet-Miner being situated in the space between the conveyor and the coal face. (The conveyor is straddled by a portal structure so that a good clearance profile is assured.) To eliminate problems of energy and water supply, a special cable guidance system was developed which is supposed to allow trouble-free supply via cables and hoses even at traveling speeds of 0.5 m/s.

The prototype built by M.A.N.-GHH-Sterkrade, subsequent to elaboration of a joint concept, exhibits the following design data:

Length..................m..	8.56
Height mined............m..	0.98
Pump drives............kW..	215
Water flow..........L/min..	162
Water pressure.......MN/m..	70
Total mass.............kg..	18,000

SURFACE TRIALS

The Jet-Miner prototype is designed for coal winning underground. For checking the overall system feasibility, a surface testing program was carried out. Except for the length, the surface test duplicated all machinery components that were used underground. A 35-m-long test rig was set up in the test facility for coal winning and coal clearance techniques at Bergbau-Forschung GmbH (fig. 5). The rig operates on a mockup coal face 13 m long and 1.5 m high. This mockup coal face had a strength corresponding to the respective values of coal prevailing in the production face envisaged.

The surface trials had the objective of testing the haulage system, the hydraulic drive system, the electric control installation, and extraction output and loading trials. The cutting test resulted in a winning performance 50 pct higher than with the first test rig. The loading capacity could also be improved. When passing horizontal and vertical undulations, the unit showed good running properties.

UNDERGROUND TRIALS

At Lohberg colliery seam R was prepared for the test under production conditions. The existing plough system had been replaced by the Jet-Miner. The coal face was 260 m long with a seam thickness of 1.45 m. The Jet-Miner was designed in such a way that it could run on any existing plough guides. Only the special guidance system for energy and water supply was custom-fitted.

Only components cleared for underground operation were used. The hydrostatic drive system used nonflammable fluids. The conveyor, Jet-Miner, machine haulage, and high-pressure pumps were controlled from a central control consol using an audiofrequency system supplied by Siemens.

All equipment used by Bergbau-Forschung was first cleared for underground operation. The following parameters are measured and recorded by UV-recorders and magnetic tape systems: Hydraulic pressure of the hydrostatic drives (measure for chain traction effort), and speed of the drives (traveling speed).

The underground tests yielded the following results:

1. The tractive efforts on the chain reached maximum values of more than 600 kN.
2. The Jet-Miner exhibited a strong climbing tendency.
3. The cutting of the roof and of dirt bands was unsatisfactory.
4. The mechanical elements, e.g., the high-pressure pumps, the hoses, the oscillating mechanism for the nozzles, the mechanical horizon control, etc., had high failure rates.

The evaluation of these results leads to the following conclusions:

1. The high tractive efforts on the chain were due to--
    A. Excessive friction within the plough guide system and corresponding high wear.
    B. Unsatisfactory cutting head performance due to insufficient water jet pressure on the nozzles due to clogging of the nozzle oscillating mechanism.
2. The reason for the strong tendency to climb is the arrangement of the lower cutting head in a 30° position from the vertical.
3. The controls of the hydrostatic drives worked unsatisfactorily in terms of synchronization so that uncontrolled chain slackening occurred.

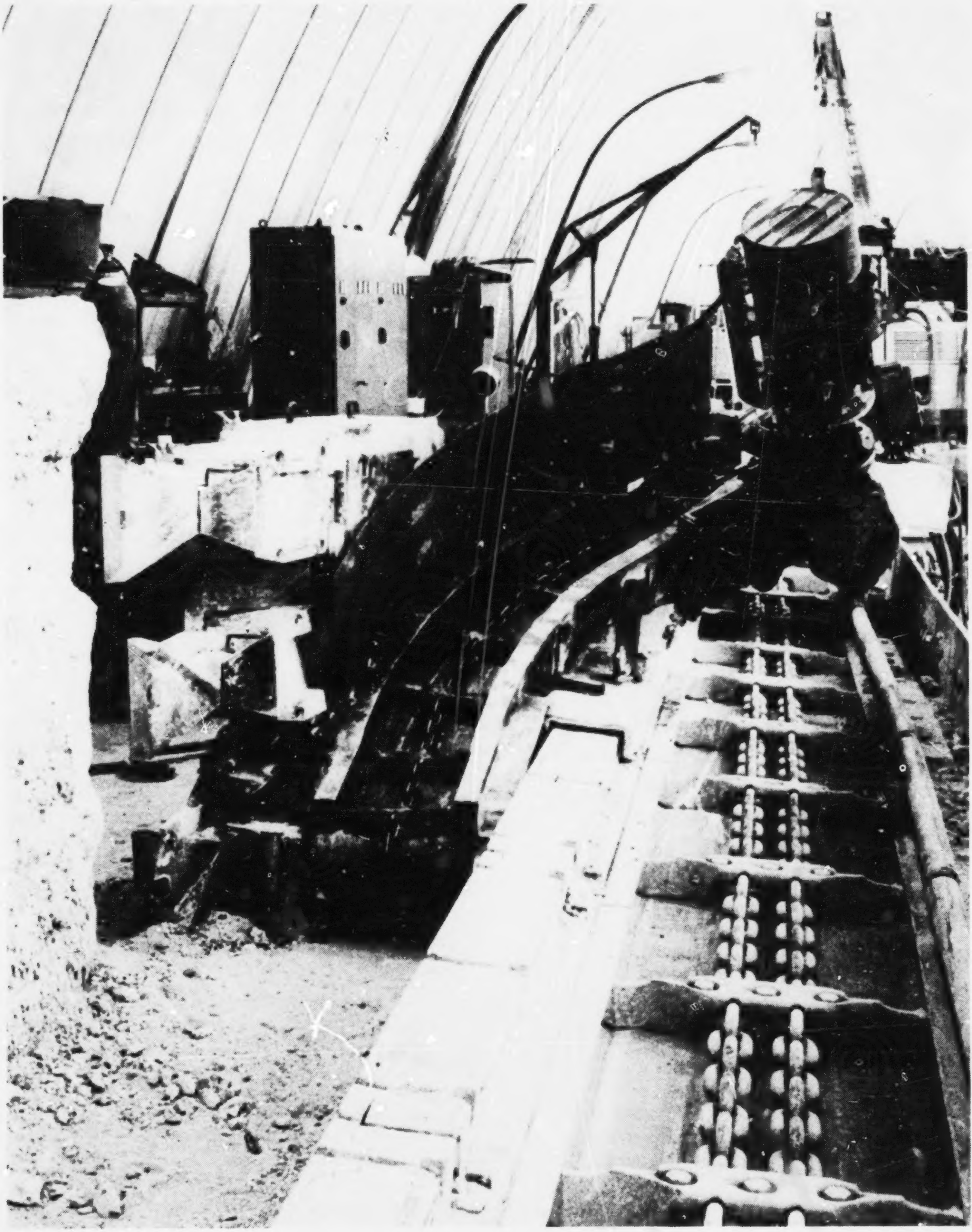

FIGURE 5. - Jet-miner test facility.

PRESENT SITUATION

Following the underground tests, the results were evaluated and an extensive investigation of cutting heads was conducted. As a result, several modifications were made to improve cuttability at long nozzle-face distances by nozzle design, water conditioning, smoothing of the high-pressure flow upstream of the nozzle, improved water supply, and modification of the oscillating system.

Figure 6 shows the optimum pressure developed for various nozzle designs compared with the data from the original water supply system. When using curved jet tubes, the oscillating system, however, causes, almost inevitably, a strong pressure drop at larger standoff distance.

PERFORMANCE SPECIFICATIONS

When designing the Jet-Miner the following performance specifications should be met according to present knowledge:

1. Cut over the total worked thickness, including roof and floor.
2. Establish horizon control by adjustment of the floor cutting system.
3. Provide yaw control for the cutting heads.
4. Provide retractability of the trailing head from the face.
5. Load cutoff mineral in wide-web cuts at low traveling speeds.
6. Guide machine over snaking conveyor.
7. Prevent clogging of cutting heads and plough guides.
8. Provide improved hydrostatic drive control.

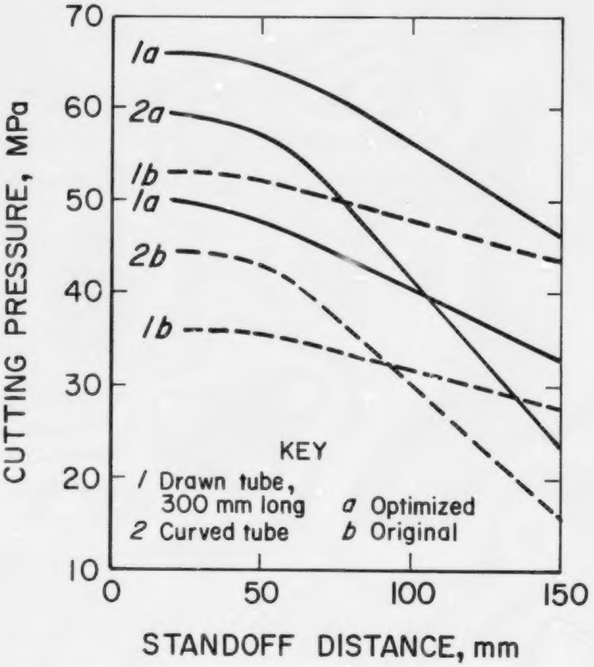

FIGURE 6. - Cutting forces of various jet tubes (tube 7 mm, nozzle 1.95 mm).

At present, tests are being run on mockup coal faces in an attempt to meet these sometimes contradictory performance specifications. The tests mainly concentrate on loading properties, cuttability, horizon control, and clogging. Another aspect concerns the reliability of machine elements, accessibility to the individual components, and monitoring and controlling the integrated system, namely, the plough, the conveyor, the drives, etc.

THE DEVELOPMENT OF THE IMPACT PLOUGH

In the past, the function principle of the pneumatic pick, i.e., mechanical cutting by impact tools, turned out to be extremely efficient. The successful use of hydraulically activated percussive hammers, generally known under the term "impact ripper," in road headings, leads to the consideration of this technology also for coal winning machinery. Figure 7 shows the function principle of an impact plough. According to the direction of travel, the leading impact hammers of a plough system are activated from a powerpack (P = 200 kW, pressure supply p = 2,000 psi) with an impact frequency of 5 to 10 Hz.

The impact hammers assure a high compressive-stress buildup at the tip of the pick. Accordingly, stone can be cut and faults can be worked through. Furthermore, the system can cut wide webs. For experimental use and testing of this technology, an experimental unit (fig. 8) was set up and tested on a mockup coal face. The following problems were encountered:

1. Guidance of the tool at high transverse forces.
2. Hammer array.
3. Loading of the cutoff mineral.
4. Machine guidance along the coal face.
5. Unsatisfactory function of the hammers.

After extensive testing, the reasons for the deficiencies were identified, and remedial action could be taken. At present the experimental unit has been reconstructed, checked, and will be run in an experimental face underground. We expect this development to be successful.

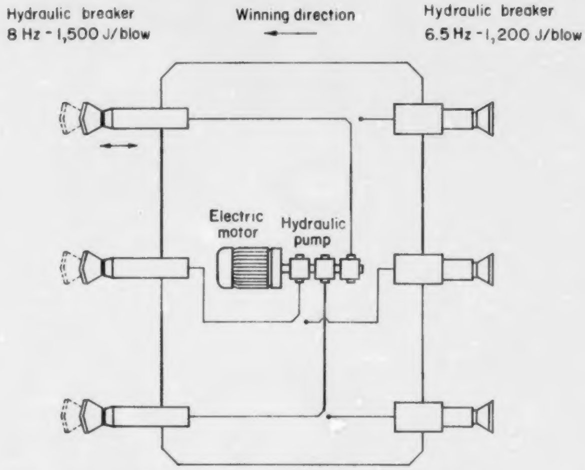
Hydraulic breaker
8 Hz - 1,500 J/blow
Winning direction
Hydraulic breaker
6.5 Hz - 1,200 J/blow
Electric motor
Hydraulic pump

FIGURE 7. - Impact plough, principle diagram.

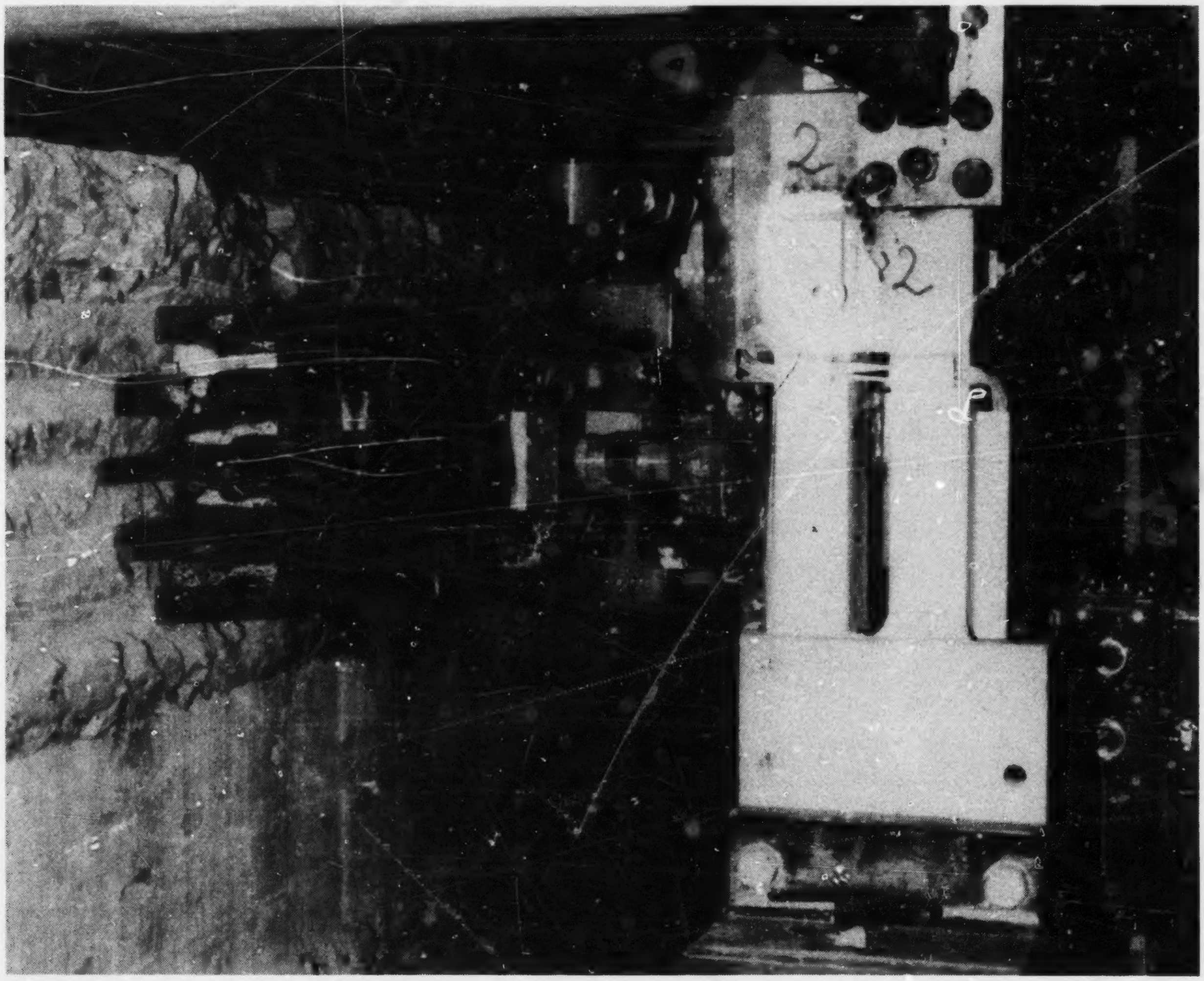

FIGURE 8. - Impact hammer, experimental unit.

BASIC INVESTIGATIONS ON VIBRATION TECHNOLOGY

At present, basic investigations are being run within Bergbau-Forschung in view of using vibrations to fracture minerals. For these investigations a test rig was set up on which a cutting tool has been arranged and onto which vibrations are induced by a hydraulic ram (fig. 9). The cutting tool is mounted to a measuring frame which is pulled along the coal face by a chain. The hydraulic ram is activated by a powerpack via servovalves. The oscillation frequency can be adjusted between 0 and 50 Hz. Furthermore, various wave forms, e.g., sinus, sawtooth, or rectangular, can be selected.

The cutting tests are run on various tool designs and cutting angles as well as on mockup coal of varying strength. Cutting forces, feed thrust, and transversal forces are measured as assessment parameters for the cutting performance of this technology. From the cutting force plot on figure 10 it may be seen that in the case of a nonactivated tool (frequency = 0) a maximum tractive effort on the chain of Fs = 70 kN is recorded for a cutting depth of b = 100 mm and a cutting tool width of 300 mm. For an identical cut, the tool vibrating at a frequency of f = 20 Hz with an amplitude of a = 5 mm, a cutting force of Fs = 15 kN was required. The cutting force reduction corresponds therefore to a factor of 4 to 5.

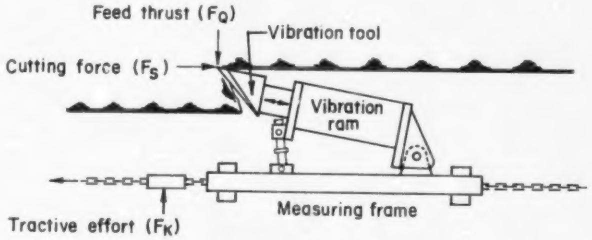

FIGURE 9. - Test rig, vibrating tools.

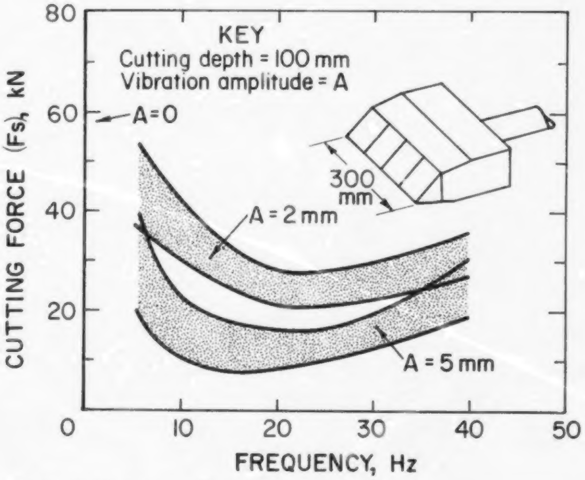

FIGURE 10. - Cutting forces of vibrating tools.

These positive test results gave us reason to develop, in a first phase, a hydraulic system suited for underground testing. For the next development phase it is intended to set up an experimental unit for surface and underground testing.

SUMMARY

Looking at present requirements for new activated coal-winning machinery, the necessity for such developments is pointed out.

The pattern followed for the required basic investigations, the setup of experimental units, and the construction of prototypes is discussed.

The present stage of development and application of high-pressure water-jet cutting technology, of impact plough systems, and of vibration technology is outlined. Specific problems as well as application limits are explained.

THE WATER JET PLOW

By David A. Summers[1]

INTRODUCTION

This meeting takes place on the longest day of the year. It is, therefore, timely as well as pertinent to begin by wishing you "Heddwych" from the UMR-Stonehenge, which was dedicated by a druid of Geffodd of the British Isles at sunset last night (fig. 1).

This topic is pertinent because the 52 rocks of this half-scale model were carved, in their entirety, by high-pressure water. The trilithons of the inner circle (fig. 2) stand some 16 ft high and are made of Georgia granite with a compressive strength of 30,000 psi. The rock was cut by water jets, at an average pressure of 15,000 psi at the University of Missouri--Rolla (UMR). To complete the project on time, cutting rates at least twice those of conventional cutting were required, and achieved. This is an interesting topic in its own right, and also one that is very pertinent to the subject of the meeting today.

ACKNOWLEDGMENTS

This work was funded under contract to the Bureau of Mines and the U.S. Department of Energy. The detailed design of the head was largely the responsibility of Dr. Clark Barker of the University of Missouri--Rolla, while the construction was in large measure carried out by the staff of the Rock Mechanics & Explosives Research Center. This project was very much a team effort, with input coming not only from those of us on the project, but also from the Government agencies and substantially from the industrial contacts we had with people we visited who came to see the machine work. We are very grateful and happy to acknowlege that assistance and advice.

EQUIPMENT OPERATIONAL LIFE

Most water-jet-cutting research comprises a series of tests that are of short duration and concentrate on the cutting ability of the water jets. Data on the problems apt to be encountered during the lifetime of the equipment are rarely presented. The construction of the UMR megalith required that the high-pressure equipment operate at a pressure of 14,500 psi for approximately 1,000 h. This pressure is some 50 pct higher than that normally recommended for the cutting of coal. To cut a smooth channel down through the rock, the nozzle must be fed forward after each pass across the surface. This requires that a 5-cm-wide slot be cut into the rock to ensure that the nozzle can move freely. To cut this slot, two 0.925-mm-diam jets were rotated at approximately 300 r/min. The swivel, located in an unsupported position at the top of the cutting lance, allowed this rotation, and the same unit was used throughout the cutting (fig. 3). Nozzles, that cut within 1 cm of the surface lasted around 20 h, with the major failure being because of the surrounding metal holder, rather than nozzle failure per se. Nozzle quality was not, however, consistent. Rubber hoses, rated at 40,000 psi burst pressure, held up well in the early stages of the program, but after some 600 h, several had to be replaced.

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[1] Curators' professor, Rock Mechanics and Explosive Research Center, University of Missouri--Rolla, Rolla, MO.

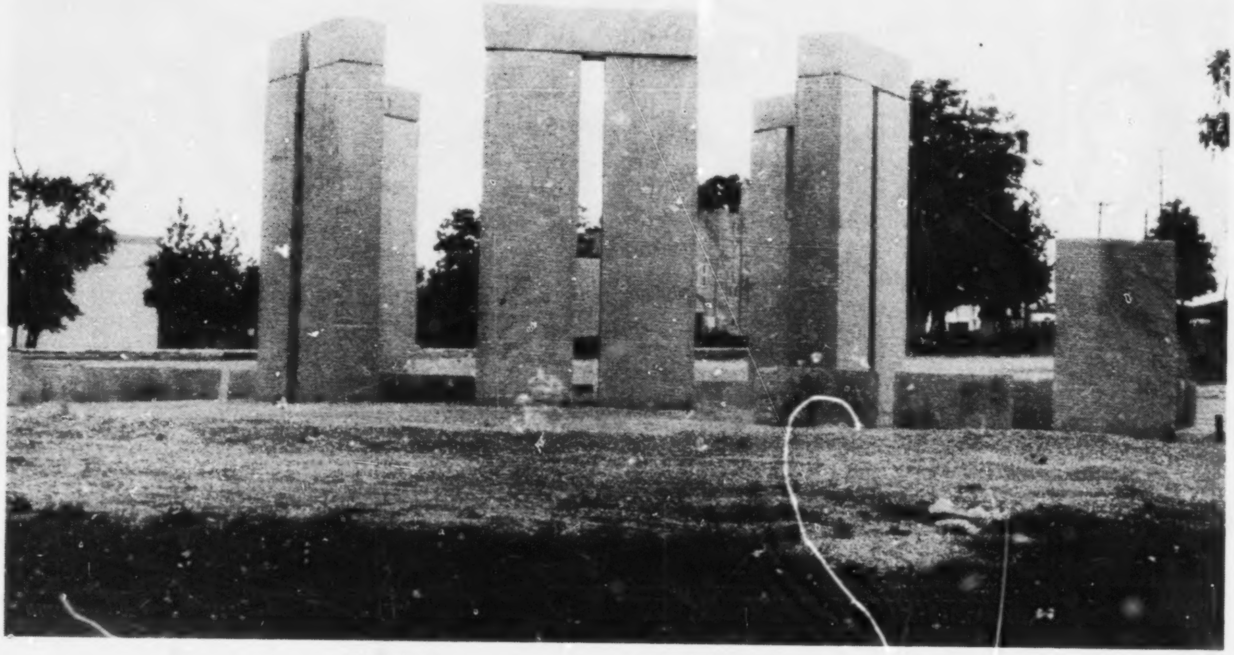

FIGURE 1. - Overview of the UMR Stonehenge.

This information is provided to show, in part, how far the reliability of the equipment has come since 1974, when the Bureau of Mines granted UMR its first contract on the Hydrominer program. Although the granite cutting unit ran for 24 h at 14,500-psi pressure on June 16-17, 1984, at that time virtually no equipment was available to run at even 10,000 psi on such a continuous basis. Within this past decade water-jet equipment has, however, come of age.

THE UMR HYDROMINER

The use of high-pressure water for cutting coal has many potential advantages, and a likely equivalent number of pitfalls for the unwary. In this brief presentation, it is not possible to cover all of these; such a discussion is given on the final report of the Hydrominer project (1).[2]

The Hydrominer is a water-jet-assisted plow. In the original concept of the device (2), water jets cut along the perimeter of the plow, cutting an access slot for the wedge head to enter and wedge off the central coal core (fig. 4). Following laboratory tests undertaken to establish the basic cutting parameters of the jet and to determine to what degree the initial design would be valid, a preliminary unit design was developed, constructed, and field-tested in a surface coal mine in the Midwest in 1976 (fig. 5). One initial change that had to be made in that program was to ensure that all the water-jet nozzles oscillated over a given cutting path. In the original conception, it was felt that the jets would cut the required depth from a fixed position on the plow body. However, because of the jet and slot interference and the blocking of subsequent jet action by the rebound of the preceding flow, fixed jets do not give the performance levels required. This work, since confirmed by the failure of the fixed-jet plow in Germany (3), led to the simplification of the device into the form used

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[2] Underlined numbers in parentheses refer to item in the list of references at the end of this paper.

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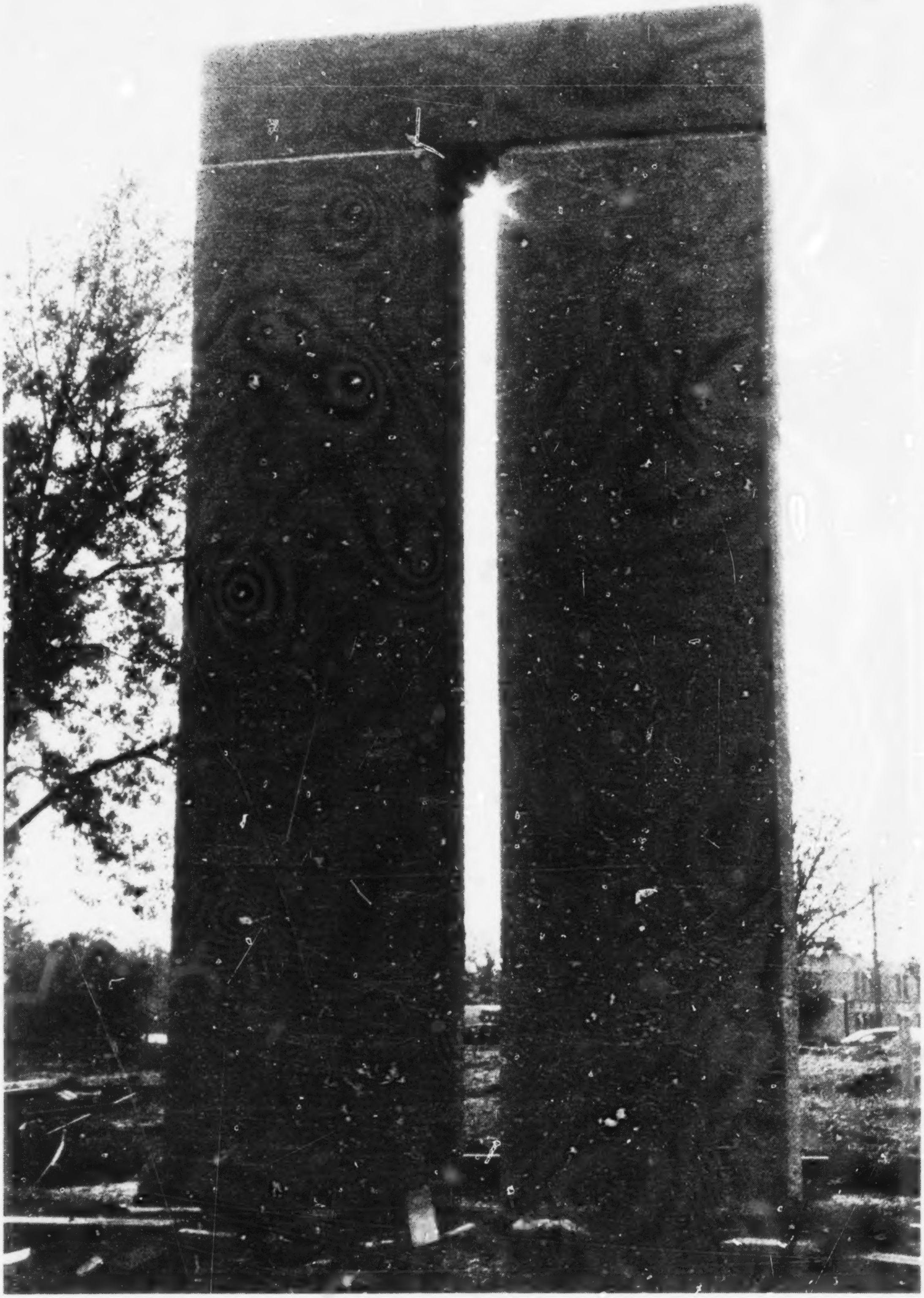

FIGURE 2. - 16-ft-high central trilithon, carved from granite by water.

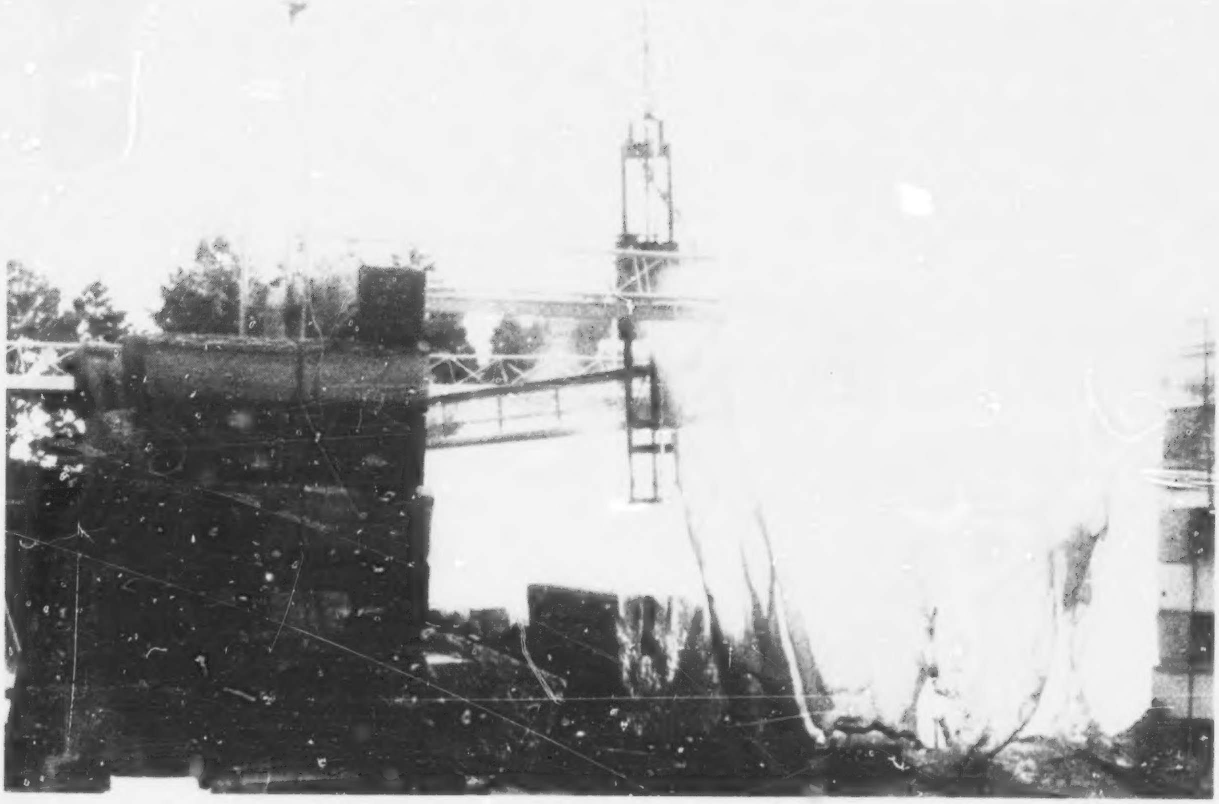

FIGURE 3. - Swivel detail from granite cutting unit.

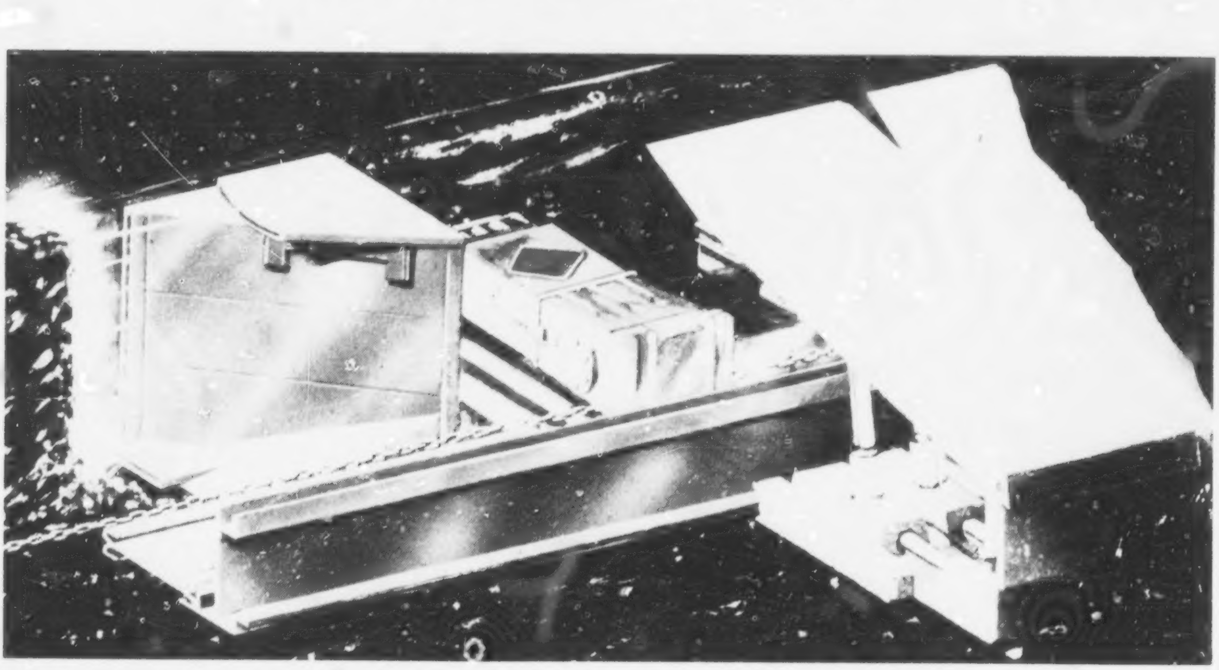

FIGURE 4. - Artist's impression of UMR Hydrominer.

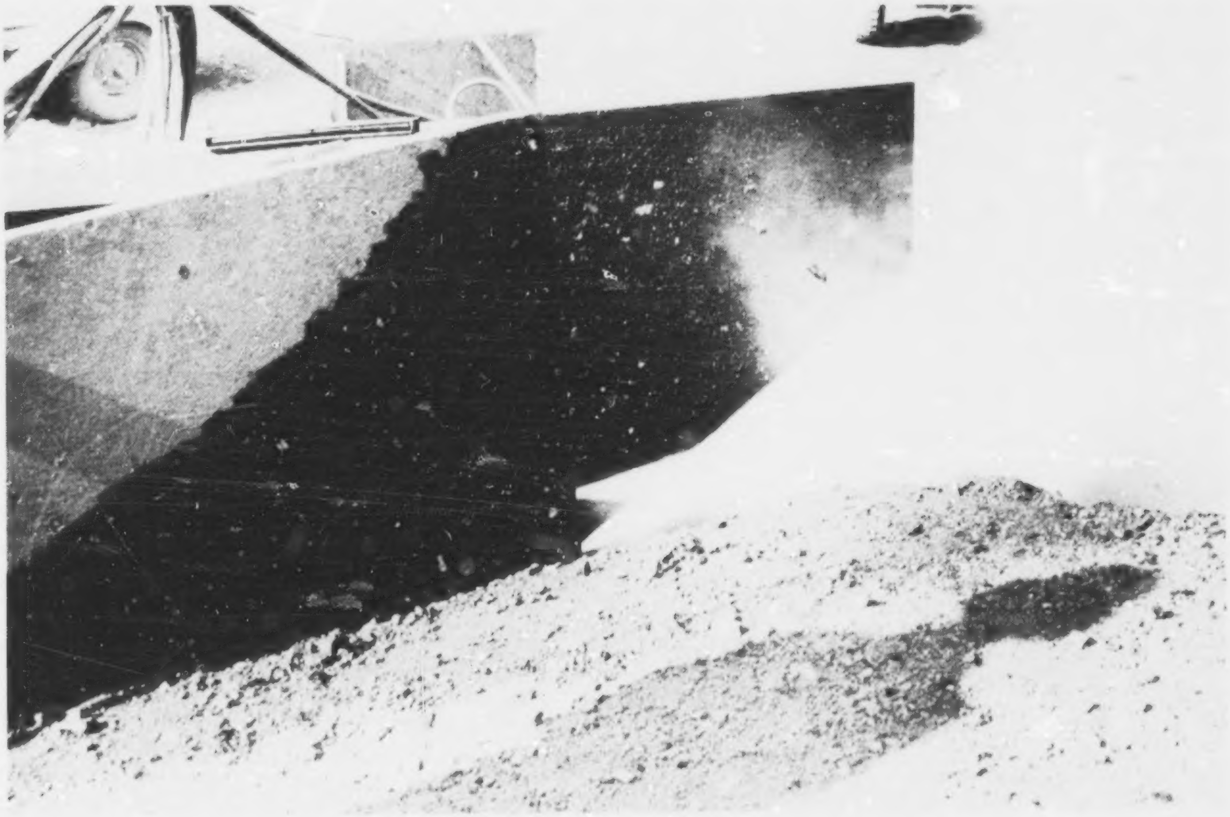

FIGURE 5. - Equipment on trial surface coal mine.

in the field trial. The results of that trial were very encouraging, and every goal set by the Bureau for our performance was exceeded. Potential advantages resulting from the use of the Hydrominer include--

1. 40-pct increase in productivity at equivalent horsepower.
2. Control over product size.--Note that larger coal means fewer losses and increase in preparation plant productivity.
3. Elimination of respirable dust problem.
4. Removal of the face gas ignition hazard.
5. Ability to increase web depth without equivalent increase in horsepower.
6. Reduction in haulage horsepower required.

As a consequence of that study a second generation head was built; concurrently an impetus was provided for the German study which has since developed (4).

The effectiveness of a water-jet-mining machine, however, is critically dependent on making the best use of the jets that cut the coal. These jets only cut a slot around the perimeter of the mass being removed (fig. 6), a technique proven feasible by the widespread use, at one time, of the Meco-Moore mining machine. For most effect, this slot must run at least 4 in ahead of the plow blade. Such a slot depth cannot be maintained unless the jets oscillate over the face of the plow, but it also requires that the jets be generated from an effective nozzle design.

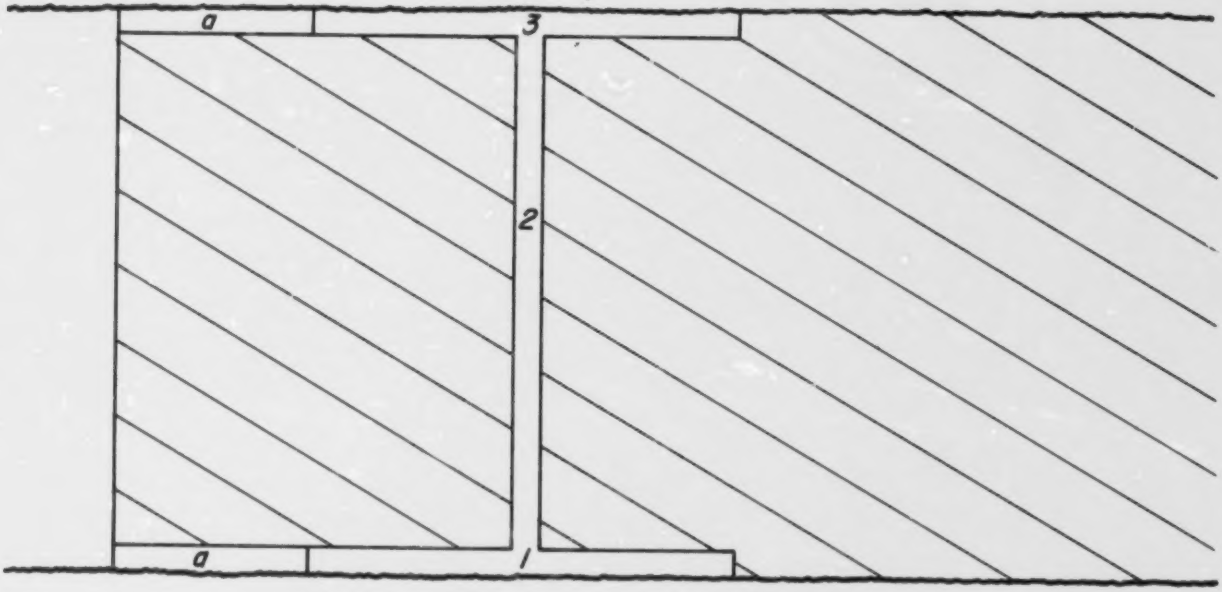

FIGURE 6. - Cutting pattern of slots for the Hydrominer.

NOZZLE DESIGN

The UMR group, and particularly Dr. Barker, spent considerable time improving nozzle design (5). It should be clearly appreciated, from the outset, that coal does not behave in a similar manner to other rock under water-jet attack. In most rock, adjacent cuts can be made up to an intervening distance of perhaps three nozzle diameters before the intervening rib disintegrates; with coal the rib is removed with a spacing between cuts of up to 5 cm.

The benefit that this gives is that it allows the use of a dual-orifice diverging jet pair to cut slots in the coal. This in turn substantially improves potential cutting performance. A single jet cuts a slot of decreasing width as it penetrates the material (fig. 7). Thus on a second pass, over the same slot, the sides of the previously cut slot erode the sides of the cutting jet so that its performance is reduced. A reduction in performance of up to 50 pct may occur on this second pass, depending on the relative efficiency and parameters under which each cut is made. If, in contrast, the flow is directed through two diverging jets, the coal between these two jets will be removed as the jets make the primary cut (fig. 8). Thus when the nozzle advances, and the second cut is now made, the jets do not meet the coal until they reach the back of the previous cut. In this manner the jets will cut the depth by which the unit has advanced, or the same depth as the first cut, depending on where the cut surface is relative to the nozzle. This relates to the decay in jet effective cutting pressure with standoff distance from the nozzle.

NOZZLE POSITIONING AND CUTTING PATH

It is important to locate the nozzles in the correct position on the plow head to achieve optimal cutting results. This pertains particularly to two aspects of the design, and leads to resolution of two potential problems. The cutting arms should be so oriented that they overlap in cutting to the full seam section, but concurrently the face angle jet should pass directly in front of the face cutting edge of the plow. This face should be a sharpened hardened metal surface,

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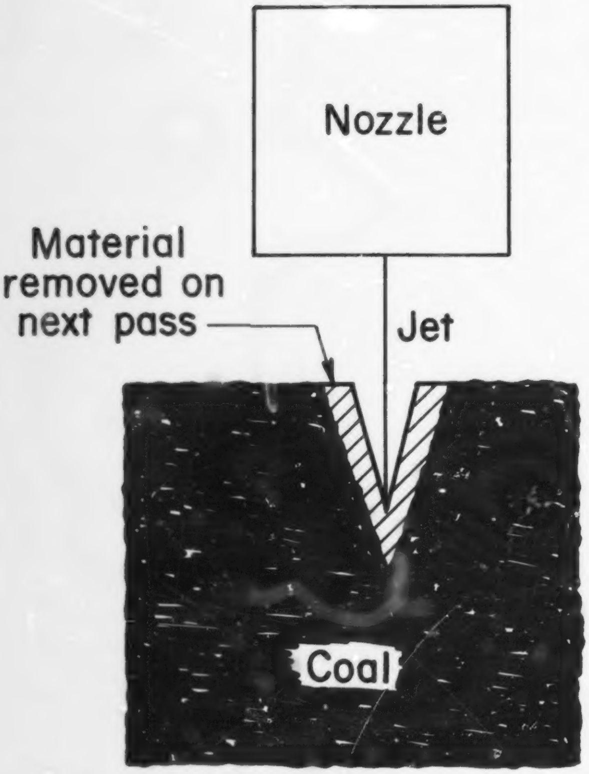

FIGURE 7. - Slot cut by a single-jet nozzle.

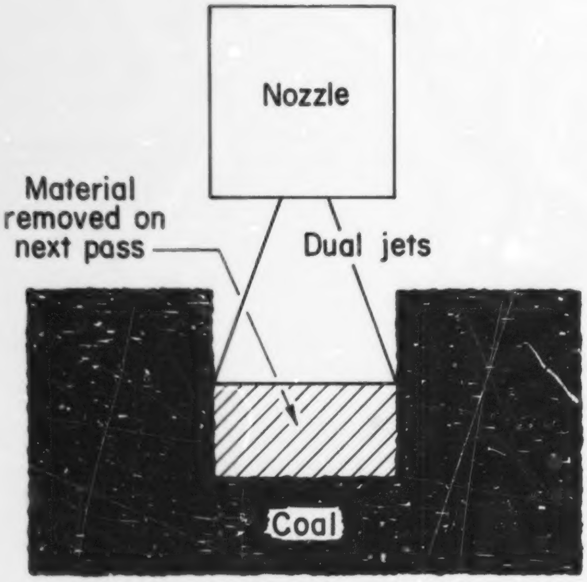

FIGURE 8. - Slot cut by dual-jet nozzle.

with the intention that the jets will normally cut a path in the coal sufficiently wide that the head can enter the slot, with subsequent contact being made on the wedge section where the angled surface will cause the main coal column to break off from the solid.

Where a layer of rock is present in the coal, the water jets will normally remove the coal from either side of the layer but will not always be able to totally remove the inclusion. Under these circumstances, the synergistic effect of the water jet acting with a metal tool (the water-jet-assist mode as it is known) can be utilized through the combination of the plow edge and the oscillating jet. By such a means the Hydrominer was able, in its field trials, to cut through >3-in-thick lenses of pyrite. It is necessary to cover the full seam section, given that one cannot predict where the bands of dirt will occur.

The second important feature is to ensure that the column of coal isolated by the vertical jets, cutting at the back of the plow, is also cut horizontally. Two different options were considered for this feature. In the original Meco-Moore design the column was broken at the bottom and half way up the section; this feature was changed, because of the smaller web which the Hydrominer takes, and also because in many coals there is a need to leave either a fixed amount of roof coal or a fixed amount of floor coal. A positive horizon definition is thus required, and therefore horizontally oscillating jets are placed to cut across the column at the roof and floor. This arm, however, does not have the major purpose of creating a cutting plane; rather the intent is to break the support column to the roof and thus transfer the abutment load from the coal, before the plow begins to fracture the coal, and load it onto the conveyor. Because of this feature the coal, at loading, is unstressed, and with no strength in tension is easily broken into fragments and loaded onto the conveyor. Because of this feature the head becomes virtually web insensitive in terms of haulage and cutting force. For example, in the trials at Moberley, the web was increased from 18 to 39 in with virtually no change in the haulage force required to move the machine down the face and to load the coal. The cutting force, through the jets, of course remains unchanged, given that there is no change in the jet system.

DESIGN OF THE SECOND-GENERATION HEAD

There were a number of substantial defects in the design of the first-generation head, which have been changed in the design of the second-generation unit. Apart from the need to substantially strengthen the head to resist the forces imposed in moving large tonnages, the most obvious feature was the decision to split the head into two modules. Each module contains a vertical oscillating arm and a horizontal oscillating arm (fig. 9) but is designed so that the two modules may be separated vertically by a set of hydraulic rams, to cope with variation in seam section (a feature we were not to pursue further in our development of this phase). The modules can also be adjusted horizontally so that either the top or bottom section of the coal can be removed first. This feature is judged important since the lower force required to break out the coal will allow the top section of the coal to be removed first and then subsequently the lower section. This will allow the lower coal a free surface to lift up into, and thus will make loading of the coal from the face a much easier operation.

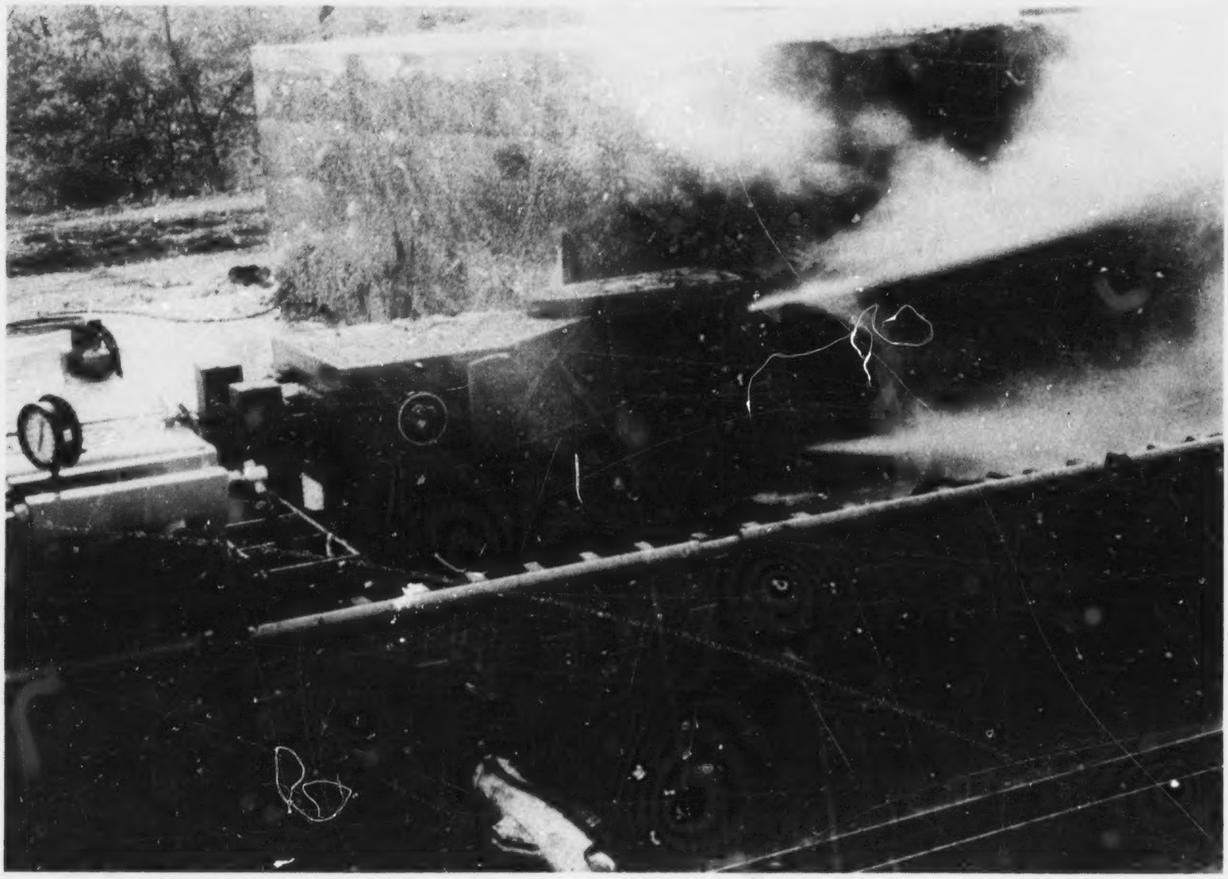

FIGURE 9. - Second-generation cutting head.

The interior features of the head were simplified, in a manner detailed in the contract final report (1), so that a simple robust head was constructed. The nozzles developed were of the more advanced design and were fitted with guards to ensure that only a slot wide enough for the jets to escape existed on the head of the unit. Concurrently a flushing system was incorporated so that, at the end of each path, the jet struck a small metal surface which directed the jet back into the head, to flush any coal chips that had migrated back into the head out of the path of the arm. A second subsidiary circuit was built into the head, but not used, that would allow a low-pressure flow into the arm compartment to flush any large accumulation of coal out of the ports provided for that purpose in the design.

REFERENCES

1. Barker, C. R., and D. A. Summers. The Development of a Longwall Water Jet Mining Machine (DOE contract AC01-75ET12542, Univ. MO--Rolla. July 1981, 199 pp.; NTIS, DOE/ET/12542-T1.

2. Summers, D. A. Water Jet Coal Mining Related to the Mining Environment. Paper in Proceedings of Conference on the Underground Mining Environment (Rolla, MO, Oct. 27-29, 1971). Univ. MO Press, 1972, pp. 183-194.

3. Henkel, E. H., and T. Kramer. In-Seam Trials With the Hydrohobel. Paper in Proceedings of the First U.S. Water Jet Symposium (Golden, CO, Apr. 7-9, 1981). CO Sch. Mines Press, 1982, pp. III-5.1 to III-5.7.

4. Henkel, E. H. Development Work for Coal Winning Technology. See pp. 40-48 of these Proceedings.

5. Barker, C. R., and B. P. Selberg. Water Jet Nozzle Performance Tests. Paper in the Fourth International Symposium on Jet Cutting Technology (Univ. Kent, Apr. 12-14, 1978). BHRA Fluid Engineering, Cranfield, Bedford, United Kingdom, 1978, pp. A1-A12.

DESIGN REVIEW OF JARVIS CLARK JETBOLTER

By William C. Griffiths[1]

INTRODUCTION

The transfer of technology from the world of research to the world of industry is always a challenging task, especially when more than one organization is involved. In December 1982, Jarvis Clark saw the potential of the work being done in water-jet drilling by research organizations under Government sponsorship and entered into a collaboration agreement with Flow Industries, a leader in this field. We took the hardware developed by them and integrated it into the first custom-designed water-jet roof bolter. When we entered our collaboration agreement the extent of field testing of the water-jet-drilling concept was a 3-month underground test involving a retrofit of high-pressure water-jet componentry onto an existing conventional hydraulic rotary roof bolter. The results of this test were so encouraging that design work on a water-jet roof bolter began in March 1983.

The jetbolter is the final result of one year's intensive design effort to integrate the high-pressure water-jet componentry with the most up-to-date hydraulic and electric systems available to the coal industry.

DESIGN CRITERIA

The design starting point was a self-imposed set of physical constraints within which all of the componentry had to be packaged for both safety and protection. These constraints were--

1. 24-in overall frame height to enable future low-coal versions to be developed with no chassis redesign.
2. 9-ft maximum overall width.
3. 24-ft maximum length.
4. Provision for adjustable ground clearance and adjustable canopy.
5. 5-ft maximum tramming height.
6. Ability to drill a 6-ft hole in a single pass in openings 8 to 12 ft high.

In addition to these physical constraints, the design had to recognize, meet, and exceed all existing State and Federal safety requirements.

Figure 1 shows the general layout within the single-piece box frame chassis and includes--

1. The operator's compartment.
2. The prime mover compartment containing electric motors and hydraulic pumps.
3. The water reservoir.
4. The hydraulic oil tank.
5. A 320-ft-capacity, self-winding cable reel.
6. The electrical controller.
7. The intensifier box.
8. Four planetary geared, hydraulically powered wheel units for tramming.

This part of the machine should remain unchanged irrespective of the seam height the unit operates in. The Automatic Temporary Roof Support System (ATRS) booms and feeds will, of course, vary with seam height, although their basic design and mode of operation should remain similar.

Figure 2 is a simplified schematic of the hydraulic oil and water circuits on the machine, from mine water supply to drill nozzle. This circuit is duplicated for the other boom.

Water enters the circuit through a reverse-flushing strainer containing a mesh element, which filters out any coarse material in the mine water supply. Between the strainer and the water tank is the first of the two 10-µm filters. The water reservoir has a 130-gal capacity and is of stainless steel construction. There are internal baffles and an external water level sight gauge. The tank

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[1] General manager, Jarvis Clark Company Limited, Coal Division, Burlington, Ontario, Canada.

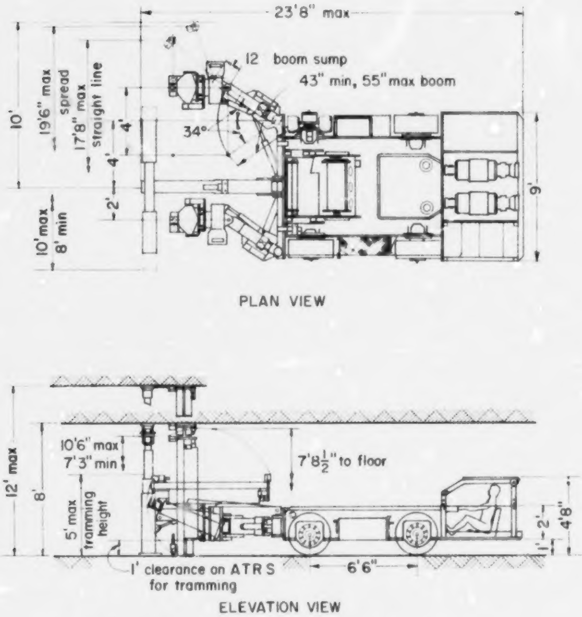
23'8" max
12 boom sump
43" min, 55" max boom
10'
19'6" max spread
17'8" max straight line
4'
4'
2'
34°
10' max
8' min
9'
PLAN VIEW
12' max
8'
10'6" max
7'3" min
7'8½" to floor
5' max tramming height
1' clearance on ATRS for tramming
6'6"
1'
2'
4'8"
ELEVATION VIEW

FIGURE 1. - General layout of jetbolter.

capacity is sufficient for approximately 4 h of drilling; however, if necessary, the unit can be run with the water hose continually connected. A rotary-gear-type water pump delivering up to 5 gal/min at 80 psi feeds the intensifiers to ensure they always work under a positive head. Excess flow from the water pump is diverted through an oil cooler back to the water tank.

The prime mover for each hydraulic circuit is a 50-hp explosion-proof ac motor with drive shafts at each end. The tramming and intensifier circuit is driven from the pump at the rear of the machine, which is a variable-volume pressure-compensated piston pump set to deliver 20 gal/min at 2,800 psi. On the front of the motor is a smaller variable-volume, pressure-compensated piston pump set to deliver 17 gal/min at 1,500 psi. This supplies booms, feeds, rotations, and hydraulic pilot signals. All four pumps

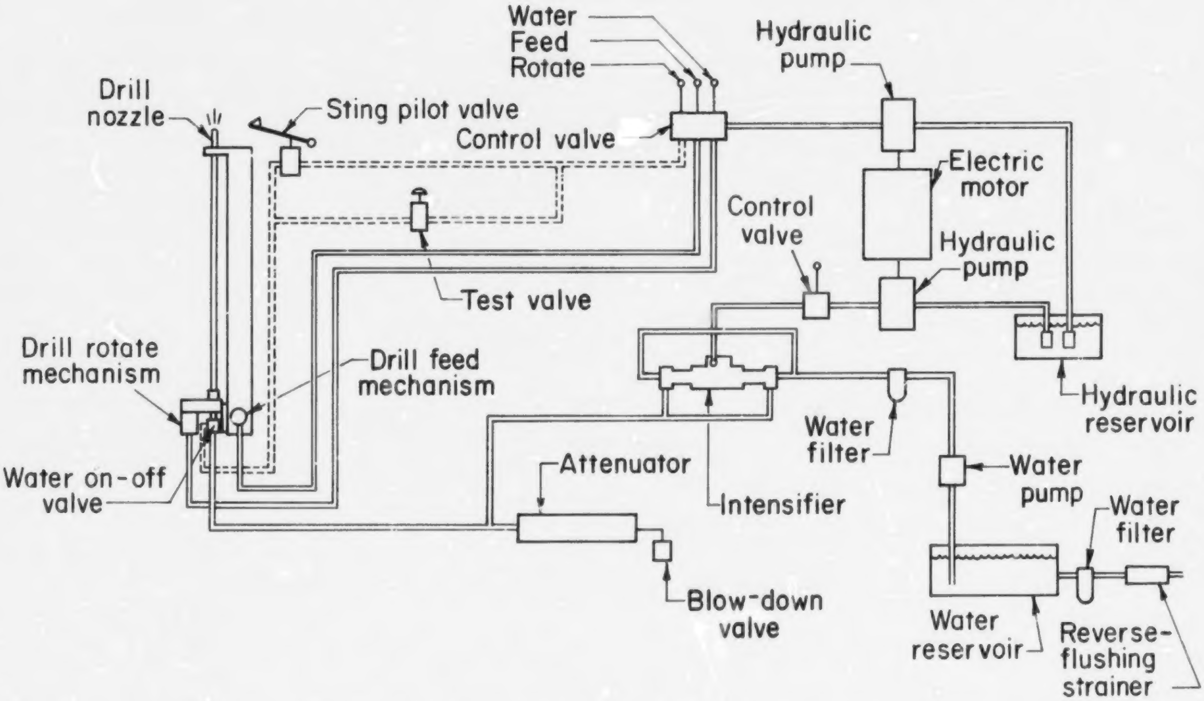
Water
Feed
Rotate
Hydraulic pump
Drill nozzle
Sting pilot valve
Control valve
Electric motor
Control valve
Hydraulic pump
Test valve
Drill rotate mechanism
Drill feed mechanism
Hydraulic reservoir
Water filter
Attenuator
Water on-off valve
Intensifier
Water pump
Water filter
Blow-down valve
Water reservoir
Reverse-flushing strainer

FIGURE 2. - Jetbolter hydraulic oil and water circuits.

draw oil from the main 150-gal reservoir through a 100-mesh suction strainer. The hydraulic system is filtered through five 6-µm filters, two in the pressure line and three in the return line.

The hydraulic and water circuits meet at the intensifier box, which is mounted on the outside of the chassis between the wheels. This box swings out on hinges to afford easy access for maintenance. Inside the box both intensifiers are on the chassis wall one above the other, together with the second water filter. Both water filters have a 10-µm rating and have throwaway cartridges made of spun polypropylene. Each filter has an internal bypass system.

The intensifier is the heart of the high-pressure system and is a stainless steel reciprocating device, comprising a double-acting cylinder with check valves at either end and a hydraulic switching device on top. This device is mechanically activated.

The principle of operation of the intensifier is shown in figure 3. At the end of the piston stroke the chamber behind the small plunger on the right is full of low-pressure water. Oil then enters the chamber behind the piston at 2,800 psi and during the course of its stroke increases the water pressure by the area ratio of the piston-plunger, which in this case is 13:1, hence 35,000-psi water. At the same time as water exits the chamber via the high-pressure check valve on the right at 35,000 psi, water enters the opposing chamber through the low-pressure check valve. The switching circuit mounted on top of the intensifier then reverses the oil flow, and the stroke is repeated. The intensifier operates nominally at 80 strokes per minute to give an output flow of approximately 1-1/4 gal/min. In industrial applications this intensifier model series has accumulated over 3 million pumping hours at pressures above 30,000 psi.

The two high-pressure lines then pass through the frame wall to the attenuator, which is a 3-ft-long gun, drilled from a stainless steel cylinder with a 2-in bore and a 2-1/2-in wall thickness. This is a surge-dampening device which smooths out the pressure spikes to provide a continuous flow of high-pressure water. This unit is placed under the oil cooler between the hydraulic oil reservoir and the cable reel.

From the attenuator, water flows to the crossover circuit. This is a series of valves enabling the two intensifier

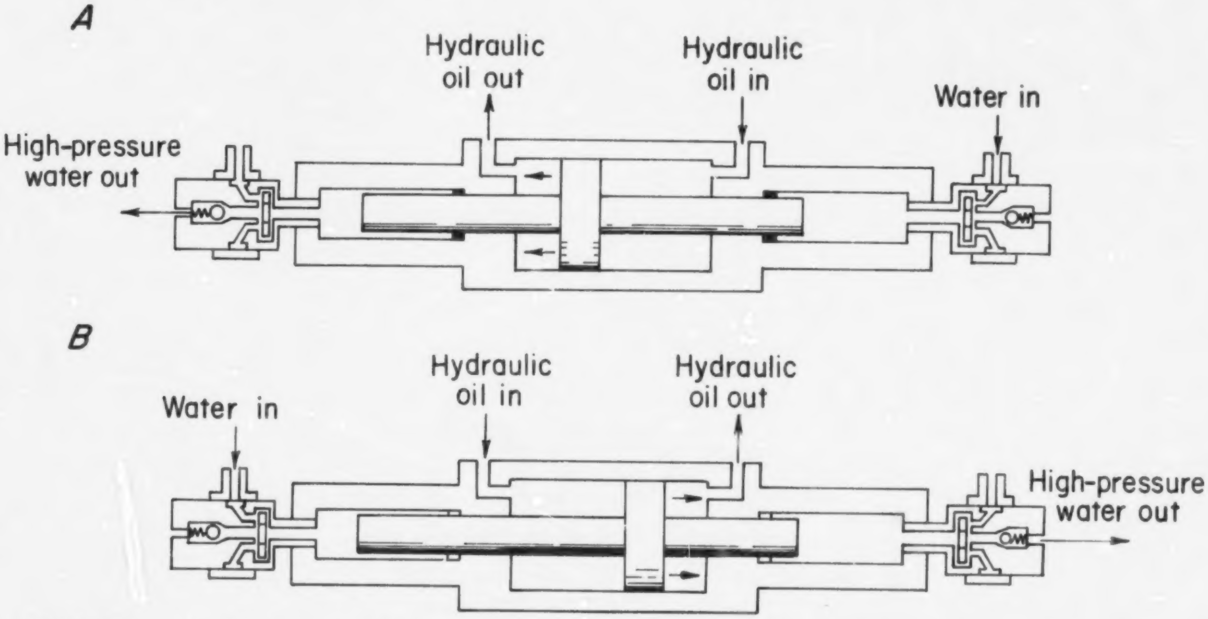

FIGURE 3. - Double-acting fluid intensifier; high-pressure water is forced to left (*A*) and right (*B*).

outputs to remain independent or to cross over or to interconnect with each other to provide higher power operation to one boom only. Up to this point all high-pressure water has been contained in steel tubing, but from the cross-over circuit to the drill mast high-pressure hose is used. All high-pressure steel tubing is painted yellow and marked "HI PRESS WATER."

The high-pressure water hose is a six-wire-braid multispiral hydraulic hose with a 3/16-in ID. Rated working pressure is 35,000 psi, and burst pressure is 60,000 psi. Fittings are crimped on with a special crimping device which virtually forms a cold weld. Hose ends and connectors use high-pressure coned and threaded connections which are rated up to 150,000 psi. As additional protection for the hose from external damage, it is sheathed in regular high-pressure hydraulic hose. A yellow plastic sheath marked "HI PRESS WATER" is then shrunk-fit over the hose assembly to distinguish it from other hydraulic hoses.

The hose is routed along the boom to the foot of the drill mast, where it is connected to the water swivel via a hydraulically operated on-off valve. This valve is connected through a safety circuit which only allows water to flow to the swivel when the mast is stung against the roof. The water swivel is located below the drill stem drive box and is thus protected from any falling debris. This water swivel contains the high-pressure rotary seal that allows the passage of high-pressure water at drill stem rotation speeds of up to 500 r/min. Seal life at this speed is 40 pumping hours, which is approximately 2 weeks' drilling under normal conditions.

Drill stem rotation is by means of a hydraulic motor and chain drive. This drive produces 40 ft·lb of torque at 500 r/min. The roof bolt inserter drive is next to the drill feed at a fixed distance of 6 in. After the hole is drilled and the stem is withdrawn, the whole mast assembly is hydraulically indexed by 6 in and the bolt is installed with the inserter drive. This is also powered by a hydraulic motor through a direct drive system. The inserter drive produces up to 250 ft·lb of torque. Both hydraulic motors and feeds are interchangeable. This system allows hands-off drilling with no delays due to drill steel changes. Bolts are placed in the inserter while the hole is being drilled. Feed is accomplished through a chain and sprocket drive, set to provide 500 lb of thrust.

The drill stem is a proprietary form of high-pressure tubing. The drill bit is threaded onto the stem at one end; at the other end, the stem is threaded into the water swivel. The drill bit is similar to a conventional tungsten carbide drag bit with set screws set into the bit matrix. Each set screw has a sapphire jewel cemented into it with an orifice drilled in it. Orifice sizes are typically in the 0.007-to 0.011-in range. A fine-mesh screen at the bit-stem interface helps protect orifice plugging from any contamination introduced into the system downstream of the filters. The sapphire jewels are normally provided predrilled and precemented into the set screws for easy replacement in the drill bit.

At the top of the drill mast, just above the drill stem collar, is a rubber boot. This collects all of the water and cuttings from the hole and diverts them down a 1-in hose to the ground at the foot of the mast. This ensures no splashback and a clean environment for the operator.

Safety was a major influencing factor throughout the design. One of the most important safety features is the stinger pilot valve. The actuator for the pilot valve is an angled plate on top of the mast which turns about a pivot point. When the mast is stung against the roof, this plate activates a hydraulic pilot valve, which in turn opens the safety on-off valve next to the water swivel. This prevents the water jets being activated whilst in a position where injury may occur to a second operator or a bystander. When the pilot valve is fully activated the plate rests against the top of the mast, thus allowing the mast to carry all the load. When the safety on-off valve is open, the normal on-off valve at the operator's station can be opened and

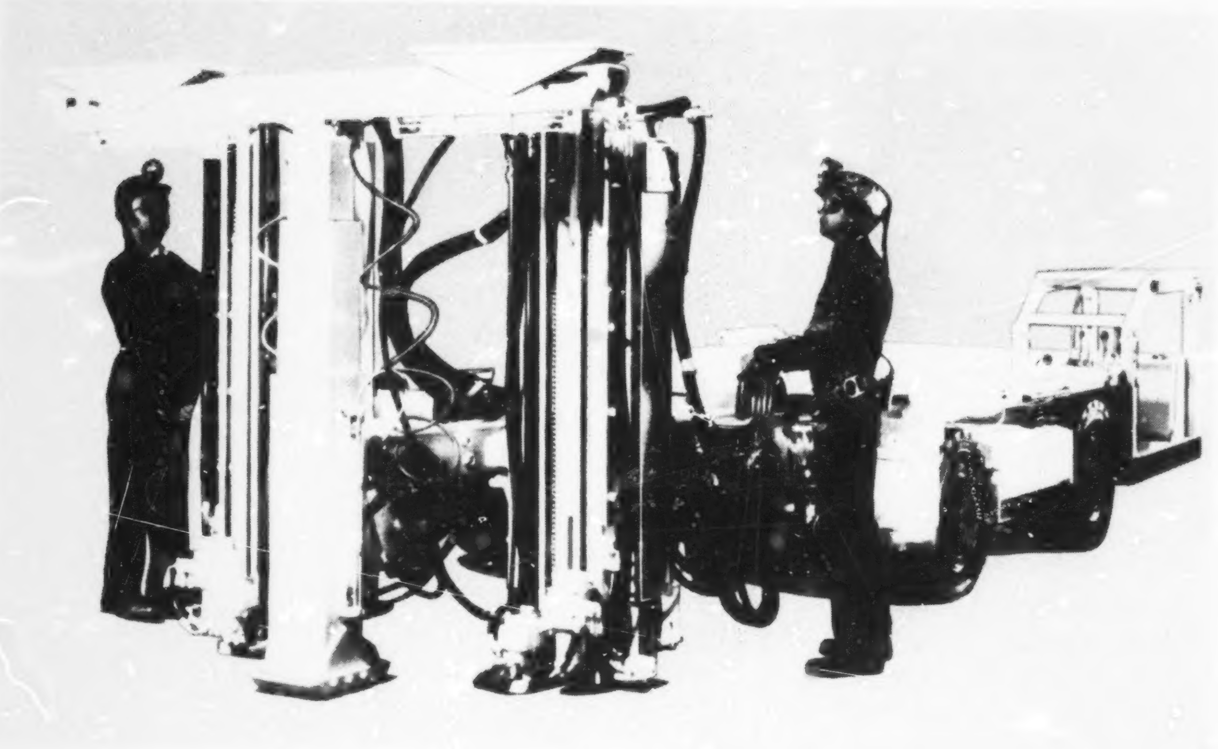

FIGURE 4. - Jetbolter prototype.

drilling can commence. As an additional safety feature this on-off valve is nondetented. There is also a manual override switch for the safety on-off valve. This must be depressed at the same time the normal on-off valve is activated. This is used only to check whether all the jets are free and operating. There is a pressure gauge at the operator's station that reads intensifier oil pressure and thus has a direct correlation to water pressure.

CONCLUSION

The jetbolter prototype, shown in figure 4, is now at a coal property in West Virginia ready to begin underground testing. In the surface drilling tests conducted in sandstone of about 12,000-psi compressive strength, some very encouraging results were obtained.

One-inch-diameter, 6-ft-deep holes were drilled consistently at penetration rates of 18 to 20 ft/min; this translates to 20 s per hole; which is about three times the rate for a conventional rotary drill. This was achieved with no dust and no water splashback, and was quiet enough that a conversation at normal levels could take place at the drill operator's station. During these tests over 350 ft was drilled with a single bit without any appreciable wear.

The potential for realizing these benefits has been known for some time from the research done in this area. The jetbolter is our attempt to make these benefits commercially available to the coal industry at a time when any potential productivity increase will realize major long-term benefits for the industry as a whole.

WATER-JET-ASSISTED TUNNEL BORING

By Dr. Levent Ozdemir[1]

ABSTRACT

This paper presents and discusses the results of a laboratory research program designed to investigate the performance improvements that can be gained by employing low-pressure water jets to assist disk-roller-type cutters. The object is to enhance hard rock boring performance through the use of water jets to increase attainable penetration rates and to lengthen cutter life, thus reducing mechanical boring costs. The technique principally involves placing a low-pressure jet directly in front of the cutter with the jet impinging the rock surface along the cutter path. The results obtained thus far indicate that water jets designed to enhance disk cutting performance in such a manner offer the potential for improved boring rates and reduced excavation costs.

INTRODUCTION

Mechanical tunnel boring technology has realized significant advances over the last two decades. A better understanding of rock failure mechanism coupled with invaluable knowledge and experience gained from case history studies has contributed to better design approaches with resultant improvements in machine performance and utilization. Today, tunnel boring machines (TBM's) are being widely used in various aspects of underground excavation with favorable economics. Their application to hard rock boring is steadily growing as improvements in current technology for machine design and fabrication continue.

Despite all these advancements, however, TBM's still have certain limitations for use in the excavation of very hard and abrasive rock formations where low penetration rates accompanied by high cutter wear generally reduce their effectiveness as a viable alternative to conventional drill and blast methods. Since no new major breakthroughs are anticipated in TBM technology in the foreseeable future, one alternative to achieving further improvements in mechanical boring performance is to utilize an auxiliary assisting mechanism as an integral part of the machine. To this end, water jets show great promise for enhancing TBM performance.

A significant amount of laboratory and field research has been carried out over the past several years to provide information for a comprehensive assessment of the technical and economic feasibility of using water jets to enhance TBM performance. The majority of this work was undertaken by the Colorado School of Mines (CSM) and by Bergbau-Forschung GmbH of West Germany. The principal goal of these efforts was to develop a workable cutting system utilizing water jets in conjunction with disk cutters for tunnel boring applications.

The research effort at CSM in water-jet-assisted cutting initially began with an extensive series of laboratory rock cutting tests using a large linear cutting machine. Small-diameter jets with pressures up to 50,000 psi were employed to create slots in the rock in front of or between the cutter travel paths. The objective was to establish "free faces" in the rock to promote rock failure and chip formation. Thus, the water jets were oriented to cut kerfs either between or along the cutter paths, and also in a combination of both. The results were impressive, showing significant improvements in the rock fragmentation efficiency of disk cutters with jet assist. To demonstrate the feasibility of the developed technique under field boring conditions, a follow-on program was initiated in which a 7-ft TBM equipped with disk cutters was modified to accept the water-jet nozzles together with all ancillary equipment. A series of field tests were run in a hard granite quarry near Skykomish, WA, and a large amount of test data for boring with and without jet assist were gathered. Overall, a 50 -to 60-pct increase in TBM penetration rate was observed when water jets were activated to assist the cutting mechanism. For some tests, the water jets were found to increase the penetration rate more than twice. Although the field tests were successful, confirming the technical feasibility of water-jet-assisted cutting, several problems likely to arise from the potential application of this concept on TBM's were also identified. Aside from safety concerns, the long-term operational reliability of the pumping equipment necessary to generate the desired pressures posed serious questions about the feasibility of the system for field application.

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[1] Director, Earth Mechanics Institute, Colorado School of Mines, Golden, CO.

Following the Skykomish field trials, tests with similar objectives were also carried out by Bergbau-Forschung GmbH of West Germany. An 8.5-ft-diam Wirth tunnel borer was equipped with high-pressure water jets, and tests were run in a sandstone quarry. Several arrangements of jet locations with respect to the cutters were investigated. The pattern involving a more or less uniform distribution of jet nozzles over the cutterhead was found to produce the greatest benefit of jet-assisted cutting. In this case, the machine thrust required to maintain a given penetration rate was reduced by about 57 pct with jet assist as opposed to mechanical boring only. Moreover, the machine power requirements were reduced by 43 pct through the use of water jets. However, the beneficial effects of water-jet-assisted cutting were found to diminish at high rates of penetration.

In spite of the fact that the application of high-pressure water jets has proven to be a technically feasible concept as a means to enhance TBM performance in hard rock, the questions related to system reliability for extended periods of operation under adverse field conditions have prevented its full acceptance and utilization by the TBM manufacturers. Another shortcoming of the developed concept was the requirement for relatively high power, which had to be added to the system to operate the water-jet pumps. Also the high jet pressures posed serious safety concerns. As a result of these potential constraints, it became apparent that the jet pressures would have to be reduced substantially to minimize power requirements, enhance equipment reliability, and improve personnel safety. These considerations eventually led to new research and development efforts with the objective of devising a low-pressure jet-assisted cutting technique for implementation on TBM's. In this aspect, several research programs have been conducted at CSM over the last 4 years. These included jet-assisted cutting in both soft and hard rock formations. In this paper, only the results of cutting tests in hard rocks are discussed.

LABORATORY TEST RESULTS

The laboratory test program for investigating the effectiveness of water-jet-assisted disk cutting was conducted on a large linear cutting machine. Tests were performed using a constant penetration mode of testing whereby cutter penetration into the rock was held constant and the cutter forces required to maintain this penetration depth were measured and recorded. All three orthogonal cutter force components (side, normal, and rolling) were measured by a triaxial load cell and recorded using high-speed digital integrators, as well as strip chart recorders. Various types of pumps, including axial-piston and triplex pumps, were employed to supply the necessary jet pressures and flow rates.

As noted previously, the jet nozzle for the linear cutting tests was positioned directly in front of the cutter and oriented to impinge the rock surface along the cutter path. The jet nozzle was securely attached to a fixture designed to permit setting of different standoff distances and jet orientation angles.

As part of various research investigations, jet-assisted disk cutting tests were carried out in samples of two rock types, granite and basalt. The granite samples were those of Colorado Red Granite, which has an average compressive strength of 21,000 psi. The basalt samples were obtained from the Hanford Site in the State of Washington, which is one of the candidate locations for a nuclear waste repository. The compressive strength of the basalt samples used for testing ranged from 25,000 to 50,000 psi.

Table 1 summarizes the test results obtained in the Colorado Red Granite with and without jet-assisted mechanical cutting. As shown in the table, test parameters involved various combinations of jet pressures and cutter penetration depths. For all tests a 0.025-in jet was used at a 2-in standoff and 3-in cut spacing. The cutter force measurements contained in table 1 are plotted in figures 1 through 3. Included in these figures are the normal and rolling forces experienced by the cutter as a function of jet pressure for the three depths of cutter penetration (0.10, 0.20, and 0.30 in). As regards the normal force, the water-jet assist is seen to produce a maximum reduction of about 25 pct within the levels of parameters tested. The rolling force is influenced to a higher degree by jet application with an average 35-pct reduction compared to mechanical cutting only. The results do not, of course, reflect the optimum cutting conditions, meaning that additional reductions in cutter normal and rolling forces appear feasible through optimization of all pertinent system parameters. In contrast to the normal and rolling forces, water-jet assist does not seem to affect the side force acting on the cutter. The side force data listed in table 1 exhibit large scatter and therefore do not allow derivation of any firm conclusions regarding this effect.

TABLE 1. - Results of water-jet-assisted disk cutting tests with jet preceding cutter in groove

(Colorado Red Granite, 15.5 in - 90° disk cutter, 0.025-in jet, 3.0-in cut spacing, 2-in jet standoff)

Cutter penetration	Jet pressure, psi	Average cutter forces, lb		
		Side	Normal	Rolling
0.10 in..................	Dry[1]	1,569	21,343	1,366
	5,000	1,843	17,066	702
	10,000	1,610	16,651	864
	15,000	1,452	17,459	742
	20,000	1,843	21,563	963
0.20 in..................	Dry[1]	4,010	32,441	2,320
	5,000	4,323	29,525	2,086
	10,000	3,607	26,273	1,916
	15,000	4,984	23,246	1,581
	20,000	4,278	28,266	1,809
0.30 in..................	Dry[1]	5,177	49,674	5,266
	5,000	7,577	42,027	4,442
	10,000	4,143	40,753	4,030
	15,000	3,069	38,344	3,721
	20,000	4,251	38,763	3,703

[1] Mechanical cutting without jet assist.

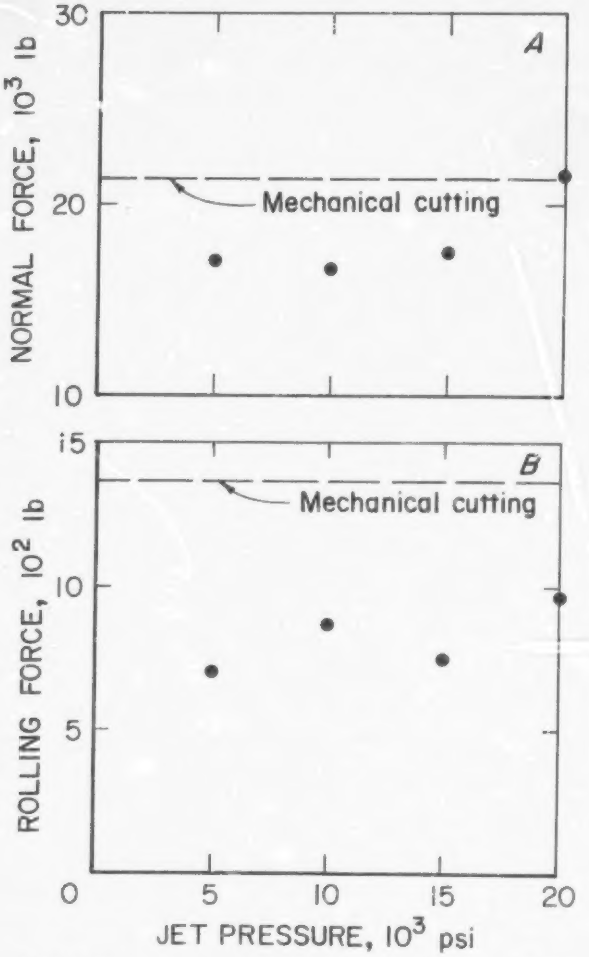

FIGURE 1. - Colorado Red Granite, force versus jet pressure, 0.10-in cutter penetration.

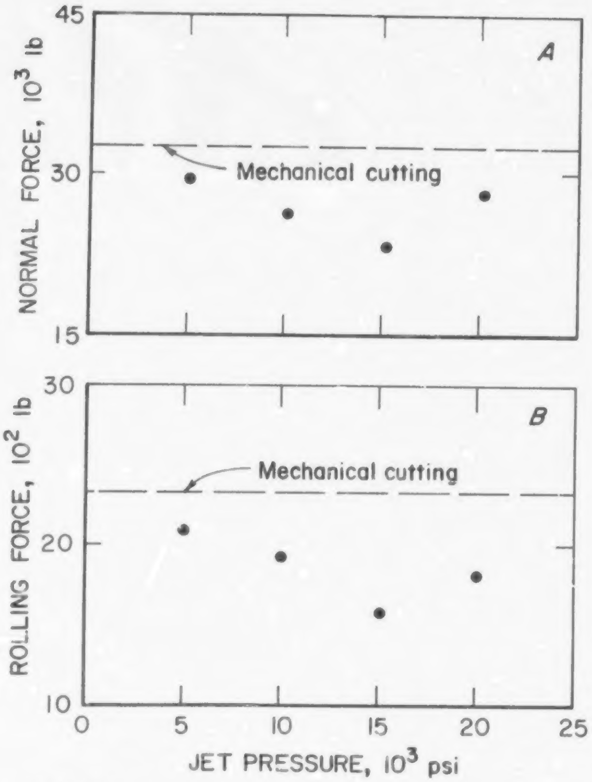

FIGURE 2. - Colorado Red Granite, force versus jet pressure, 0.20-in cutter penetration.

A series of linear cutting tests with jet assist was also run in Hanford basalts. This particular test program is still continuing; thus only test results generated to date are presented herein. Figure 4 displays the normal and rolling force measurements for various jet pressures and two standoff distances at a cut spacing and penetration of 2.5 and 0.15 in, respectively. Jet size was 0.02 in. Again, the cutter forces are reduced due to application of water jets with higher pressures and smaller standoff distances producing greater force reductions. Again, the water-jet assist influences the rolling force to a higher degree than it does the normal force. This finding is of major importance since most TBM's become torque limited before their thrust capacity is ever reached. As the rolling force on the cutters is the parameter that determines the cutting torque on a TBM, the fact that major reductions can be achieved in the rolling force component through the application of low-pressure water jets emerges as a significant benefit.

MECHANISM OF WATER-JET-ASSISTED DISC CUTTING

As discussed earlier, the initial efforts toward development of a water-jet-assisted cutting system for application to hard-rock TBM's were directed at using high-pressure jets to create kerfs in virgin rock to promote chip formation. The mechanism involved in this application was a simple slotting action that

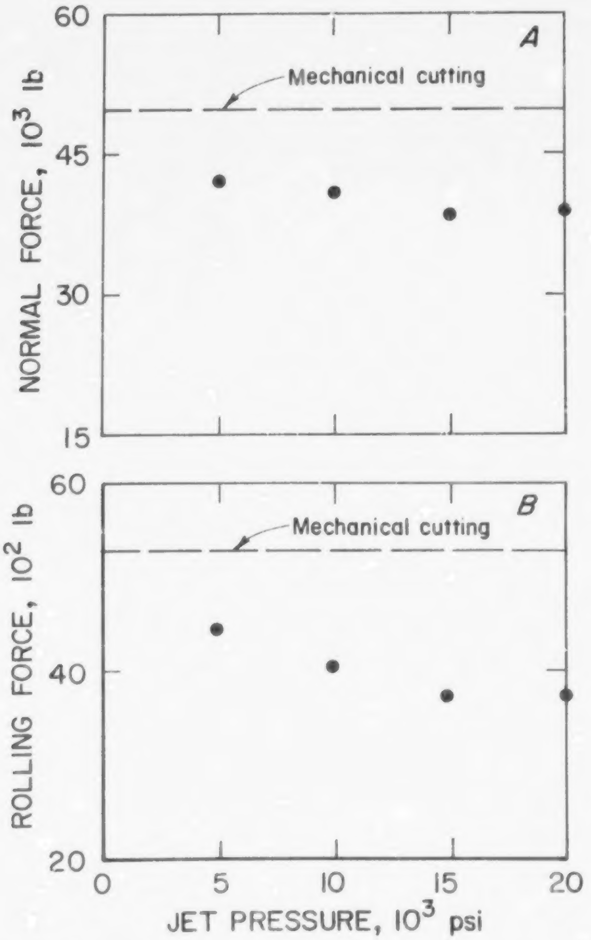

FIGURE 3. - Colorado Red Granite, force versus jet pressure, 0.30-in cutter penetration.

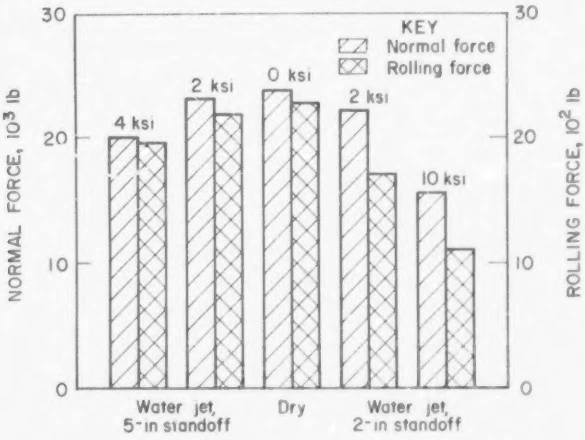

FIGURE 4. - Normal force measurements in Umatilla Basalt with and without jet assist.

made use of the high, concentrated power which water jets are capable of delivering. The mechanism by which a low-pressure jet assists the disk cutting performance is quite different, probably encompassing several factors. It is believed, however, that three factors play a major role in this respect. The first, and perhaps the most important, mechanism is the removal of the crushed zone immediately surrounding the cutter groove. Visual observations of cutter paths together with photomicrographs of the crushed and fractured zone beneath the cutter have confirmed the occurrence of such a mechanism. The second mechanism, which is believed to take place with jet assist, is the so-called hydrofracturing, whereby the water under pressure penetrates and enlarges the subsurface cracks produced due to the mechanical cutting action. Some of these cracks are enlarged and extended to a length sufficient to create additional chip formation, increasing the total yield of rock material removed by the system. Lastly, the water jet appears to lubricate the cutting path and provide a cooling effect on the cutter. This mechanism coupled with the removal of the crushed zone is believed to contribute to improved cutter ring life.

As previously stated, the principal attraction of low-pressure water jets is their low power requirements. For example, a 0.020-in-diam jet operating at a pressure of 5,000 psi generates a flow volume rate of about 0.70 gal/min and requires approximately 2.5 hp at the pump. In addition to these advantages compared to high-pressure jets, use of low pressure also improves equipment reliability and practically eliminates most of the safety concerns that are raised when considering the application of high-pressure jets on TBM's.

It is not necessarily a requirement or a feasible approach that every cutter on a TBM should be fitted with a water jet in order to achieve the desired level of improvements in excavation rates and cutter lives. A number of jets strategically placed on the cutterhead in areas where the cutting action is most difficult, i.e., the gage and center cutters, may serve the purpose and provide the degree of performance enhancement that is necessary to warrant the additional cost of incorporating water jets on TBM's. This goal can be accomplished by carrying out full-scale field demonstration tests with a water-jet-assisted TBM for determining the optimum locations of jet nozzles on the cutterhead. Such a test program can also furnish data relating to the impact of jet assist on cutter wear. It is very difficult to investigate the wear effects in the laboratory since the amount of rock cut generally is not sufficient to produce any measurable degree of wear on the cutter.

SUMMARY

The laboratory test results obtained thus far indicate that low-pressure water jets directed in the disk cutter path offer a significant potential for enhanced TBM performance. A side benefit appears to be extended cutter life, meaning lower excavation costs. Because of low pressure requirements, it is felt that a water-jet-assisted cutting system can be installed on a TBM without any major difficulty. The pumping equipment required to generate these low pressures is commercially available with proven reliability for operation over long periods of time.

Further testing is planned to improve system effectiveness and to achieve the optimal configuration of jet-assisted disk cutting. Greater benefits of jet assist than those reported in this paper appear feasible through additional optimization studies.

INVESTIGATION OF OPTIMIZING TRAVERSE SPEED OF WATER-JET-ASSISTED DRAG PICKS

By R. J. Evans,[1] H. J. Handewith,[2] and C. D. Taylor[3]

ABSTRACT

A cutterhead was designed and fabricated at the Bureau of Mines Pittsburgh Research Center to evaluate the rock-weakening effect, when using water-jet-assisted cutting, that may result from increased travel speed using moderate-pressure jets (3,000 to 9,000 psi). Two pick types, conical and flat, were analyzed for speeds ranging from 30 to 300 ft/min. The objective was to establish traverse speed threshold levels that are necessary to maintain the optimum reduction in cutting tool forces. In addition, measurements were taken to measure dust reduction when using water-jet assist. Results indicate that when employing water-jet-assisted cutting, only a negligible reduction in the rock-weakening effect was observed at higher speeds. As an added benefit, significant dust reduction was evident when employing water-jet-assisted cutting.

INTRODUCTION

The Bureau has initiated a research program in water-jet-assisted cutting to determine the improvements possible in cutting performance and health and safety. Underground coal mining machines, such as the longwall shearer and the continuous miner, cut with bit speeds ranging from 400 to 800 ft/min. To measure water-jet-assisted cutting effectiveness at higher speeds, a full-face cutterhead was designed and fabricated at the Pittsburgh Research Center. It contains six jet-assisted drag bits as shown in figure 1. The cutterhead has a 36-in diam and is outfitted to use either flat or conical bits. The bit spacing, shown in figure 2, is 2-1/2 in between each bit and double tracking at the gage bits. The cutterhead was designed to bring high-pressure water through a swivel mounted on the rear of the cutterhead. The water is then transported through holes drilled in the body of the cutterhead to the six individual bits.

APPROACH

The traverse speed cutterhead was mounted on a raise boring machine gearbox (fig. 3) which was driven by a fixed-displacement, variable-stroke hydraulic pump. The cutterhead was flange-mounted on a 5-ft section of Drilco 11-in-diam drill pipe with DI-22 threaded connections. Rotation was varied from 1/2 to 40 r/min. The maximum available thrust was 120,000 lbf. Torque was a demand function of thrust, which generated a maximum hydraulic pressure of 5,000 psig at full pump stroke. The water-jet system was powered by two 10-gal/min positive displacement triplex pumps generating a maximum pressure of 9,500 psi. Flow (pressure) control was achieved by varying the running speed of the diesel-engine-powered pump. The water jet was mounted in front of the bit and directed to impinge less than 5 mm in front of the bit cutting tip, as shown in figure 4. The water for the jet-assist cutting process was filtered through a 100-μm filter, delivered through the back of the drive train gearbox, and transported through the drill pipe and then through the high-pressure swivel, which was located in the back of the cutterhead.

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[1] Supervisory civil engineer, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

[2] Project research supervisor, Boeing Services International, Inc., Pittsburgh, PA.

[3] Industrial hygienist, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

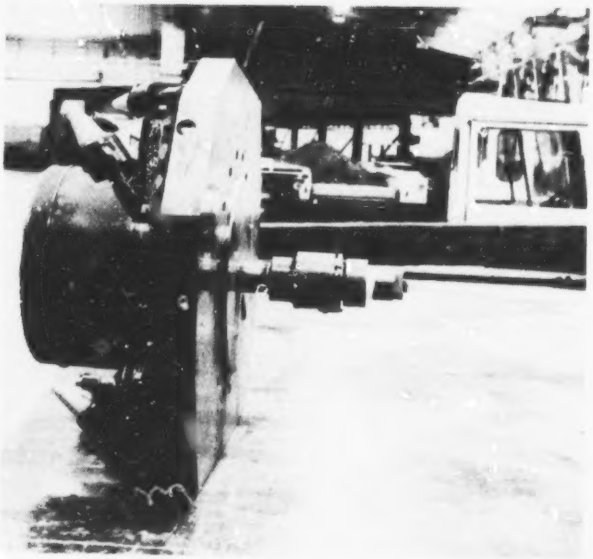

FIGURE 1. - Water-jet-assisted full-face cutterhead.

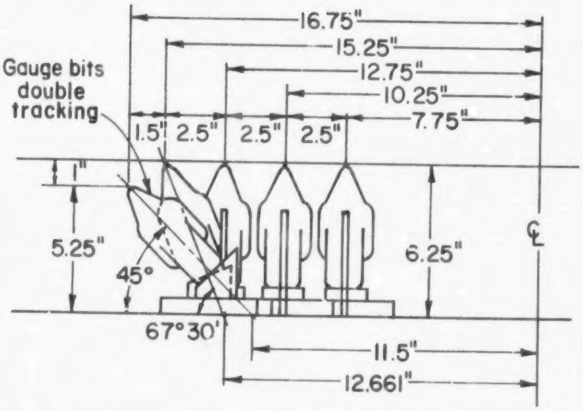
16.75"
15.25"
12.75"
10.25"
7.75"
Gauge bits double tracking
1.5"
2.5"
2.5"
2.5"
1"
5.25"
45°
6.25"
℄
67°30'
11.5"
12.661"

FIGURE 2. - Cutterhead bit spacing (dimensions in inches).

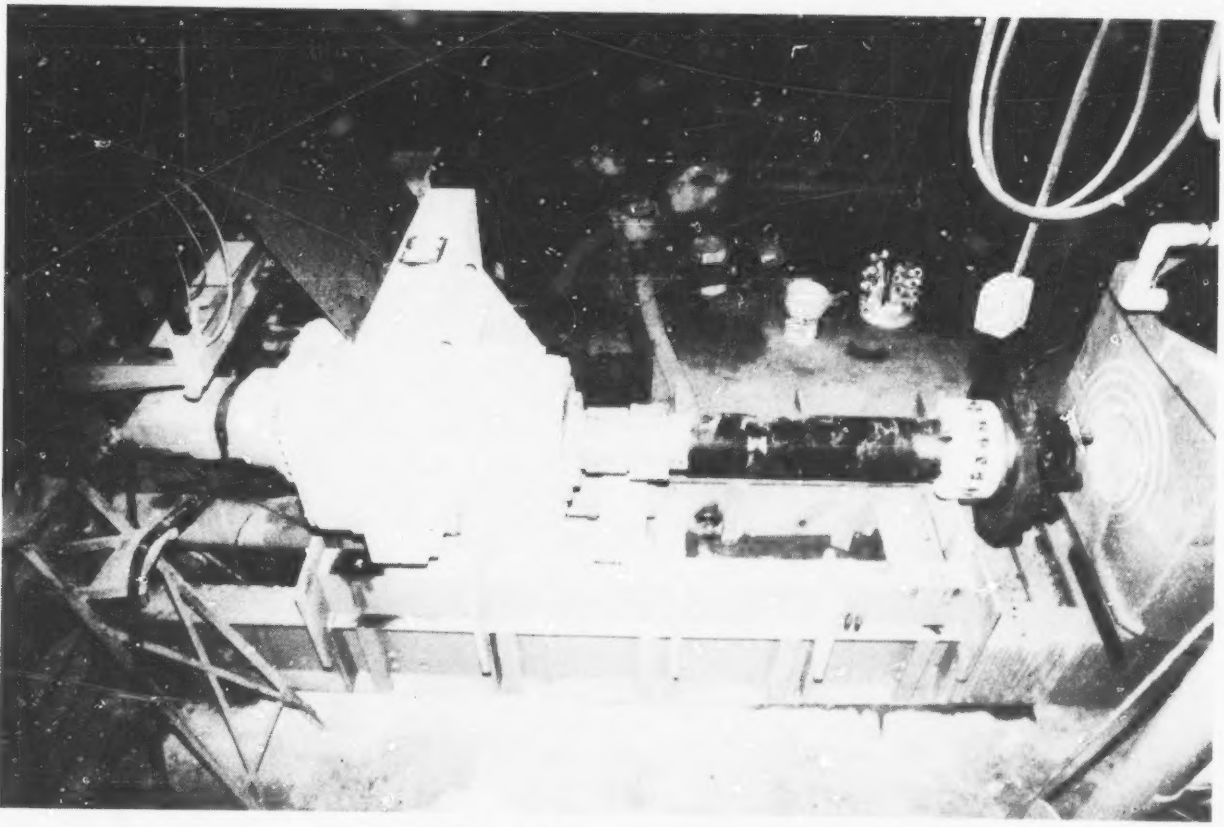

FIGURE 3. - Traverse speed cutterhead.

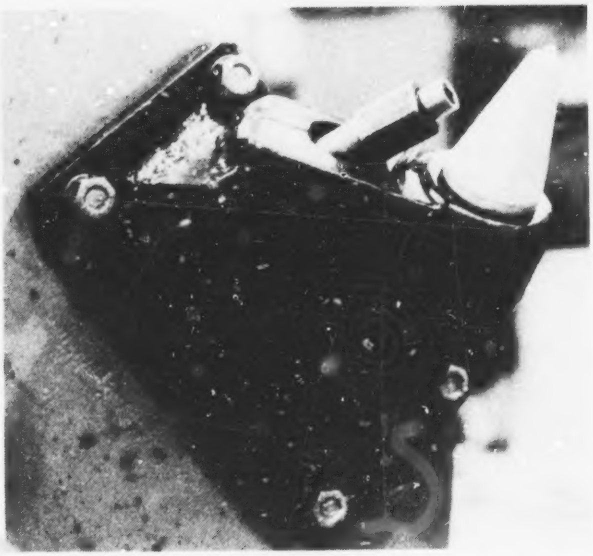

FIGURE 4. - Water-jet-assisted cutting bit and nozzle.

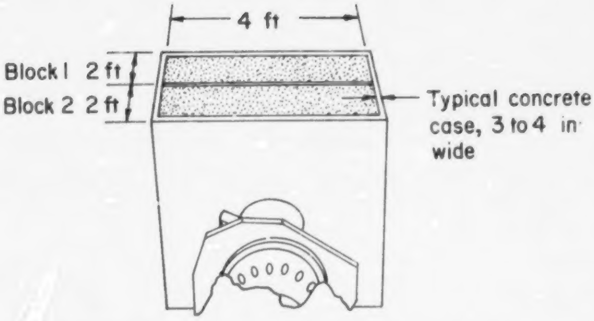

FIGURE 5. - German sandstone test block, unconfined compressive strengths: Sandstone, 19,000 psi; concrete, 6,000 to 7,000 psi (est.).

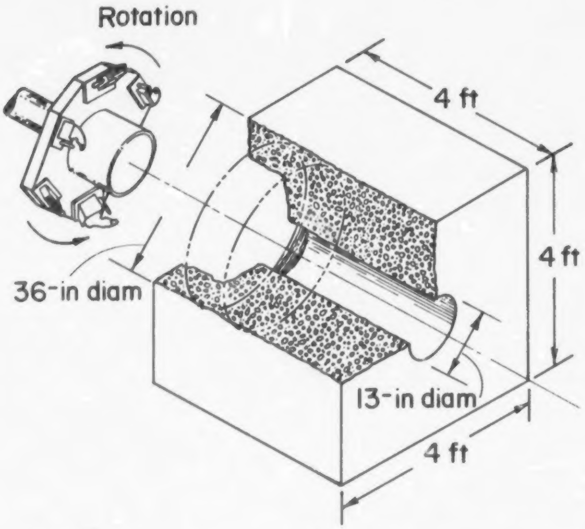

FIGURE 6. - Sandstone block and traverse speed cutter test setup.

The test material was a German sandstone with a compressive strength of 19,000 psi, a bulk density of 156.6 lb/ft^3, and 50- to 55-pct quartz content. Two 4- by 4- by 2-ft-wide blocks of this material were mounted on the test stand and cemented together with a 3- to 4-in layer of concrete around the outside, as shown in figure 5. A 13-in-diam pilot hole was drilled through the block to guide the cutterhead as it cut through the block. The cutterhead was equipped with a pilot fixture that fit into the pilot hole as shown in figure 6.

Dust levels were measured while cutting dry and with water-jet assist by drawing a portion of the dust generated from the cutting surface into a dust box. While in the box, respirable dust was separated from nonrespirable dust using two 10-mm nylon cyclones and sampling heads. Two RAM-1 real-time dust sampling instruments were used to draw respirable dust from the cyclone sampling heads and to continuously measure the dust concentrations. The concentration data from each instrument were recorded by a dual-pen strip-chart recorder. The areas under the recorded curves were compared to determine the relative quantities of dust generated when operating with and without water-jet assist.

RESULTS

Today, nearly all laboratory and some field tests are conducted at a constant depth of cut (DOC) with variable force rates. However, in actual practice, all mechanical mining machines operate with fixed force rates and variable force or penetration. The traverse rate tests conducted here were closer to actual practice than to laboratory testing.

The most significant observation was that the German sandstone could not be cut without water-jet assist. Figure 7 shows the results when cutting dry for less than 1 minute. The conical bit was worn to the point of being unrecognizable. When cutting dry, grinding steel rather than cutting rock was apparent. However, when using 6,000-psi jet assist, large chips were cut as shown in figure 8 with much less bit wear. Over the traverse speed range of 35 to 300 ft/min, no change in water-jet-assisted cutting efficiency was noted.

To measure efficiency, the use of energy volume (EV) as a measure of rock boring rate was proposed by Ross and Hustrulid[4] in 1972. This EV value was used in this study to evaluate the rock-weakening effect.

$$EV = \frac{\left(2_{\pi} \times N \times To\right) + \left(T \times \frac{AR}{60}\right)}{0.6_{\pi}\ D^2 \times AR}$$

where AR = advance rate of cutter into the rock sample, ft/h,

N = revolution rate of cutterhead, r/min,

$EV = \frac{\text{Energy}}{\text{Volume}}$ = energy per unit volume of in situ fractured rock, (in·lbf)/in^3,

To = cutterhead drive torque, ft·lbf,

T = system thrust on cutterhead, lbf,

and D = diameter of cutterhead or test bore, ft.

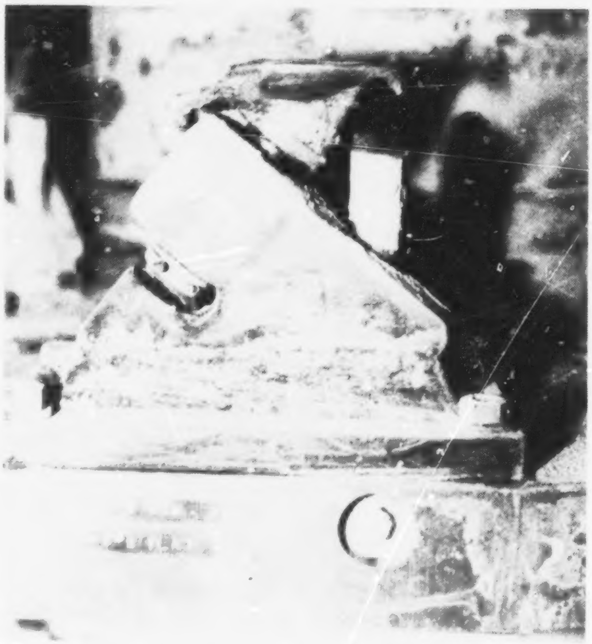

FIGURE 7. - Dry cutting of a 19,000-psi sandstone with a conical pick.

Without using water-jet assist, the energy volume (EV) rate was greater than 200,000 (in·lbf)/in^3 with an instantaneous advance rate of less than 0.75 ft/h as shown in figures 9 and 10, respectively. However, when employing water-jet assist at 6,000 psi, the energy volume rate was less than 35,000 (in·lbf)/in^3 with corresponding advance rates greater than 3 ft/h (figs. 9-10). The fastest advance rate, 88.5 ft/h, was achieved when using water-jet-assisted cutting at 6,000 psi. The EV was 1,150 (figs. 9-10), and the traverse rate was 40 ft/min.

There was a noticeable difference in efficiency when nozzles became clogged. One test had a partially plugged jet nozzle operating at 0.26 gal/min which resulted in an EV of 77,600 (in·lbf)/in^3 (fig. 9). This indicated that nozzle flow rates of at least 1 gal/min must be sustained for optimum cutting of German sandstone.

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[4] Ross, N., and W. Hustrulid. Development of a Tunnel Boreability Index (U.S. Bur. Reclamation contract 14-06-D-6849, Dep. Mining, CO Sch. Mines). Feb. 1972, 351 pp.; NTIS REC-ERC-72-7.

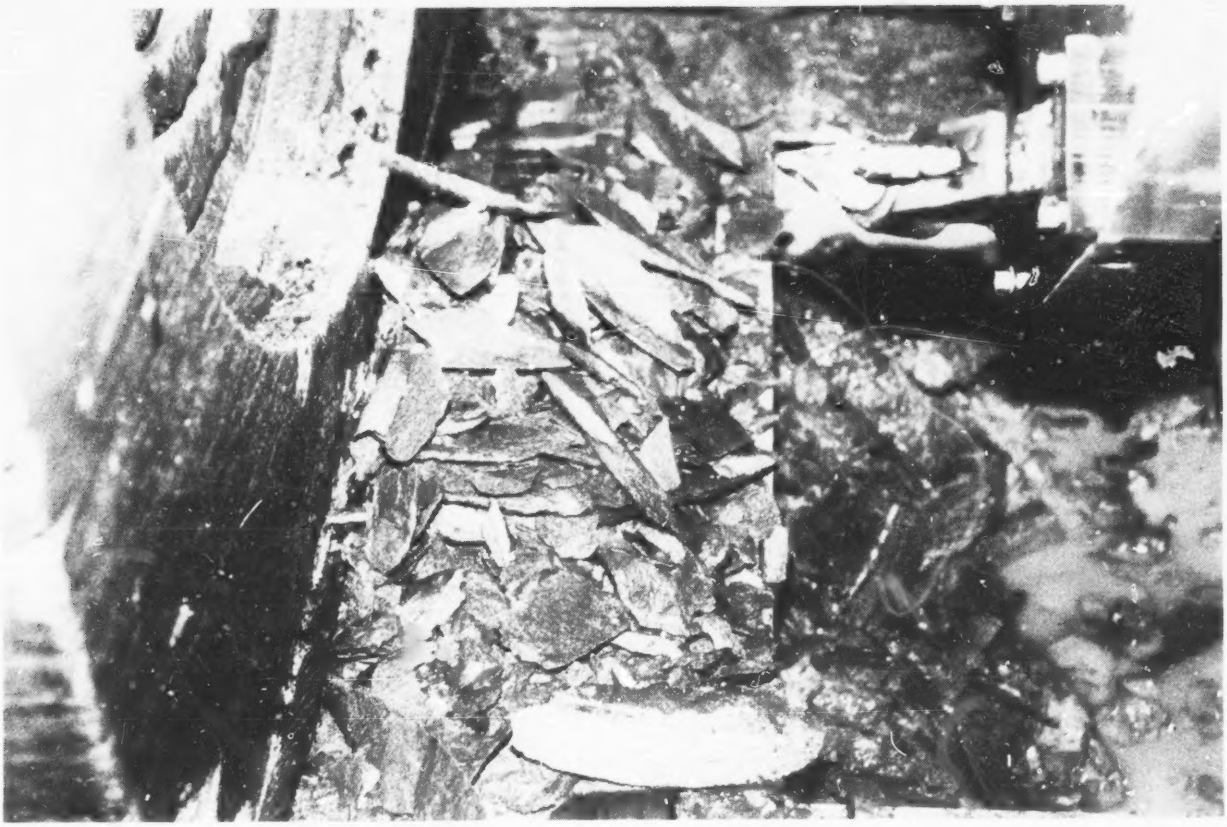

FIGURE 8. - Rock chips when cutting with water-jet-assist.

Three tests with an advance rate in excess of 20 ft/h had a large departure from the rest of the data, which were all less than 14 ft/h as shown in figure 10. The reasons for these higher advance rates are not obvious. As shown in figure 11, advance rate is plotted as a function of rotation rate. With a fixed thrust force, the advance per revolution steadily decreased nonlinearly as the rotation rate increased. Industry has always believed there is a linear relationship between rotation rate and advance rate. It has been demonstrated that advance rate can be increased by deeper DOC (in/r) or by increasing the rotation rate. However, some other phenomenon caused advance rates in excess of 20 ft/h, as shown in figure 10. Too few data exist to explain this phenomenon.

In the paper by Ross and Hustrulid,[5] for efficient cutting it was proposed that the average EV, expressed as (in ·lbf)/in^3, would approximate the average unconfined compressive strength of rock, expressed as lbf/in^2). The quantity was proposed as a measure of cutting efficiency. Since dry cutting was obviously not efficient, only wet cuts were evaluated as shown in table 1 to identify the average EV for all jet tests using both conical and flat bits. Although the flat bit was 19 pct less efficient than the conical bit, the flat bit produced the highest net advance rate. The reason for this is beyond the scope of this report and warrants more study in the future. Average EV of all water-jet-assisted

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[5] Work cited in footnote 4.

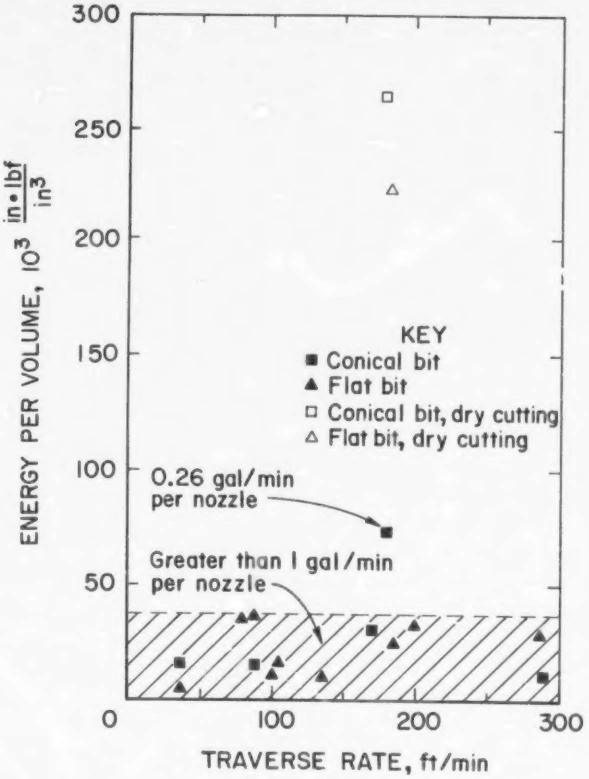

FIGURE 9. - Cutting of 19,000-psig quartz sandstone.

testing was 19,490 (in·lbf)/in^3. The reported average unconfined compressive strength for the German sandstone was 19,000 psi (at CSM by Ropchan),[6] suggesting a reasonable confirmation for the Ross and Hustrulid hypothesis that EV approximates unconfined compressive strength for efficient cutting.

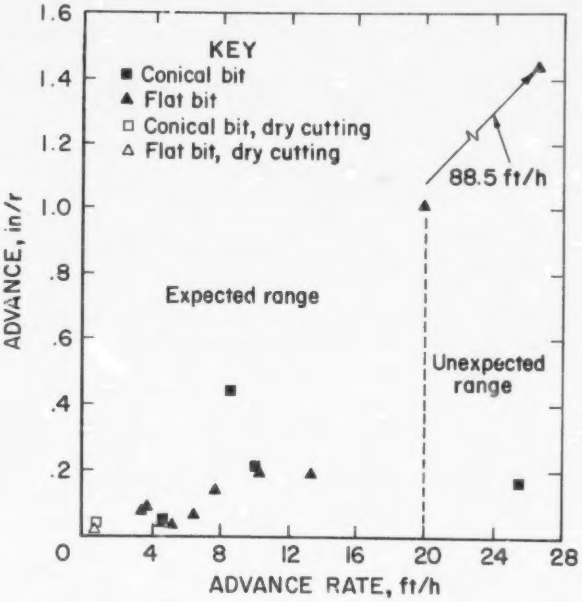

FIGURE 10. - Advance versus advance rate.

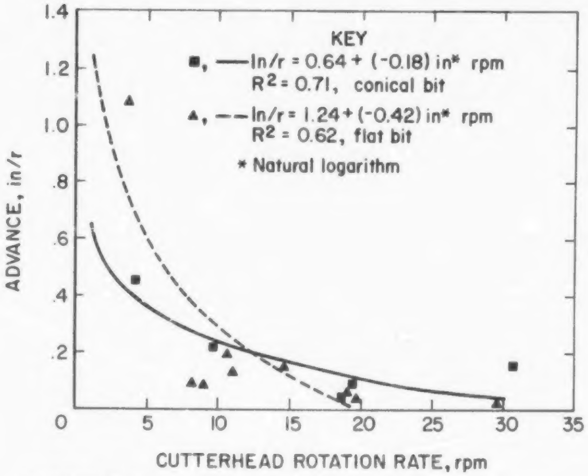

FIGURE 11. - Advance cutterhead rotation rate.

TABLE 1. - Energy volume relations with water-jet assist

Conical bit, model 070, average of 4 tests.........	(in·lbf)/in^3..	16,768
Flat bit, model K-107, average of 10 tests.........	(in·lbf)/in^3..	20,579
Average of all 14 tests...........................	(in·lbf)/in^3..	19,490
Reported average unconfined compressive strength of German sandstone....................................	lbf/in^2..	19,000

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[6] Ropchan, D., F. D. Wang, and H. J. Wolgamott. Application of Water-Jet-Assisted Drag Bit and Pick Cutter for the Cutting of Coal Measure Rocks (U.S. Dep. Energy contract ET-77-a-01-9082, CO Sch. Mines). Apr. 1980, 120 pp.; NTIS DOE/ET/12463-1.

To further confirm the test results, scalar and force relations, and calculation assumptions, a comparison was made with previous testing conducted in the German sandstone in 1980.[7] This comparison is shown in table 2. Although there were slight differences in water pressure and DOC, normal, cutting, and resultant forces were in good agreement for the conical bit. Ropchan did not test the flat bit. This confirms that scalar relationships can be established for the forces reacting on a single cutting tool and on an interactive array of such cutting tools. A significant departure from the Ropchan tests was the spacing between interactive cutting tools. Ropchan used a tool spacing of 1.5 in, whereas the spacing used here was 2.5 in. With nearly the same cutting tool force reactions, the tests conducted here produced 167 pct more in situ rock volume at the same bit force or EV rate.

TABLE 2. - Cutting of German (19,000-psi) sandstone with conical bits

Test	Force, lbf		
	Normal	Cutting	Resultant
Single-tool, by CSM:[1]			
Dry cutting........	3,860	3,501	5,220
5,000-psig water jet..............	2,042	2,340	3,121
Multitool, by BuMines:[2] 6,000-psig water jet...........	3,850	2,340	4,500

[1] Colorado School of Mines; depth of cut was 0.5 in at a 1.5-in tool spacing.

[2] Calculated from gross system forces reacting on an array of 6 cutting tools; depth of cut was 0.454 in at 2.5-in tool spacing.

During the water-jet-assisted tests, data describing several operation functions were simultaneously monitored and recorded. The dependent or controlled function were--

FN(KLBF) = Normal or thrust force in thousands of pounds,

RPMs = Cutterhead revolutions per minute,

PW = Water pressure, psig.

Independent functions were--

INCHES = Advance in inches of the cutterhead into the test rock over the test period in seconds,

FT(PSIG) = Torque force measured as a function of the hydraulic gauge pressure, psig,

RF = Volume rate of water jet flow, psig.

One conclusion reached in this study is that there is a minimum threshold of thrust below which the German sandstone cannot be bored. This threshold was not reached for dry cutting and was obviously much higher than that required using water-jet assist.

Tool wear, after advancing less than 1 in into the test block, was excessive, as indicated by the conical bit shown in figure 8. All six cutting tools failed in this dry test. When water-jet assist was used, only occasional tool failures occurred.

Dust sampling results shown in figure 12 indicate that dust concentrations were

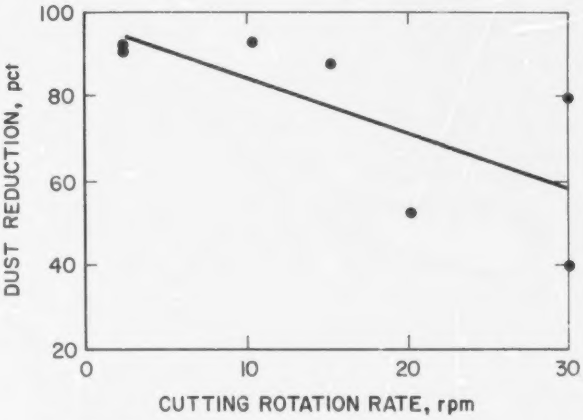

FIGURE 12. - Dust reduction using water-jet-assist with flat bits (compared with dry cutting) as a function of cutterhead rotation rate.

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[7] Work cited in footnote 6.

reduced 60 to 85 pct when using water-jet assist versus operating dry. The percentage reductions for these tests (conducted with 6,000-psi water pressure, 30,000-psi thrust, and flat bits) increased as the cutting head rotation speed was reduced.

CONCLUSIONS

The German sandstone was far more difficult to cut than originally expected. Dry cutting was impossible. Water-jet-assisted cutting with 6,000 psi resulted in dramatic improvement. No measurable degradation in rock-weakening effect was found over the tested traverse rate range of 35 to 300 ft/min in German sandstone.

The following are additional pertinent results:

1. With water-jet-assisted cutting, the EV was nearly equal in value to the unconfined compressive strength of rock, indicating that cutting was in the efficient EV range.
2. Water-jet assist was obviously effective in reducing bit wear and cutting tool forces.
3. EV level for all dry cutting was in excess of 200,000 (in·lbf)/in^3.
4. EV levels averaged 19,490 (in·lbf)/in^3, using 6,000-psig water-jet assist at flow rates in excess of 1 gal/min and 0.6-mm jet nozzles.
5. Force reactions measured on a single jet-assisted cutting tool in German sandstone by Ropchan compared favorably with those forces calculated on the interactive array of cutting bits tested by the Bureau of Mines and Boeing Services International.
6. Scalar force-rate relationships can be established between a single cutting tool and an interactive array of cutting tools.
7. The maximum instantaneous advance rate recorded on one test was 88.5 ft/h.

OPTIMIZATION OF WATER-JET SYSTEMS FOR MINING APPLICATIONS

By Dr. James M. Reichman[1]

INTRODUCTION

Mining depends upon the ability to efficiently cut and drill rock so that it can be economically excavated and processed. Ideally, the most efficient mining operation would be continuous. Thus, much is contingent upon the longevity and reliability of the equipment used. The need to extend machine life is emphasized by the negative effects of cutter and bit wear and, indirectly, decreased equipment reliability due to the higher loads required at wear points. In the past, attempts to improve machine life have focused on the "hardening" of working parts. However, metallurgy and engineering are rapidly approaching the limits of present technology.

An alternative to "hardening" of mining equipment is to develop a cutting technique that minimizes abrasive wear, reduces the required mechanical cutting force, or decreases the amount of rock cutting or drilling needed to effect breakage. The use of water jets with mining equipment is one method of achieving these goals. The optimization of this approach is the subject of this paper.

Water jets can be adapted to mining applications in various ways, including pure water-jet cutting, water-jet cutting with mechanical assist, mechanical cutting with water-jet assist, and water-jet cutting with abrasives. The pertinent parameters involved in pure water-jet cutting are shown in figure 1. Water-jet cutting produces narrow kerfs in the rock. To remove all the rock, kerfs must be made close together; as figure 2 indicates, rock type dictates kerf spacing. Rock type also determine kerf depth and cutting effectiveness.

Water-jet cutting with mechanical assist uses water jets to cut kerfs at a fixed spacing and then employs mechanical force to break the rock between the kerfs. Uncut ridges may be broken using a drag-type cutter. In this method the water jet accomplishes the major cutting task, while the mechanical cutting is secondary.

In techniques that employ mechanical cutting with water-jet assist, the mechanical cutting force is generally sufficient to cut the rock. The water jets are used to reduce the required cutting force, either by weakening the rock or by improving the cutting conditions. As shown in figure 3, the water jet can weaken the rock so that it fails in tension. The water jet can also be used to clear the cuttings away from the bit, permitting the machine to apply high stress directly to the rock.

The use of a water jet with an entrained abrasive adds a new dimension to water-jet cutting. The introduction of a high-velocity abrasive particle (fig. 4) extends the cutting depth by a factor of 5 or more over a pure water jet. In addition, the sensitivity of the water jet to various rock types is reduced.

The following sections discuss some applications of the various water-jet techniques. To achieve the performance goals and the most economical system, it is important to optimize the use of the water jet for each application. This optimization procedure will also be discussed.

WATER-JET APPLICATIONS

PURE WATER JETS

The high specific energy required to excavate large amounts of material using pure water jets makes this technique energy intensive. In many cases the inhomogeneity of the material

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[1] Director, High Pressure Technology, Flow Industries, Inc., Kent, WA.

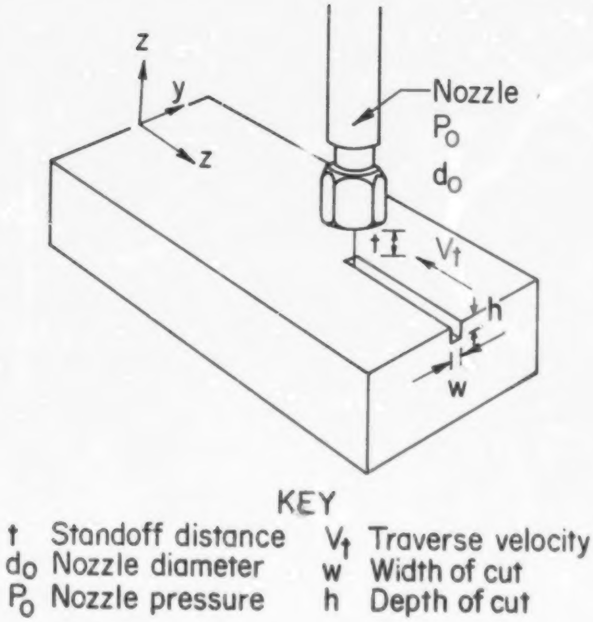

z
y
z
Nozzle
P_0
d_0
t
V_t
h
w
KEY
t Standoff distance
d_0 Nozzle diameter
P_0 Nozzle pressure
V_t Traverse velocity
w Width of cut
h Depth of cut

FIGURE 1. - Water-jet cutting parameters.

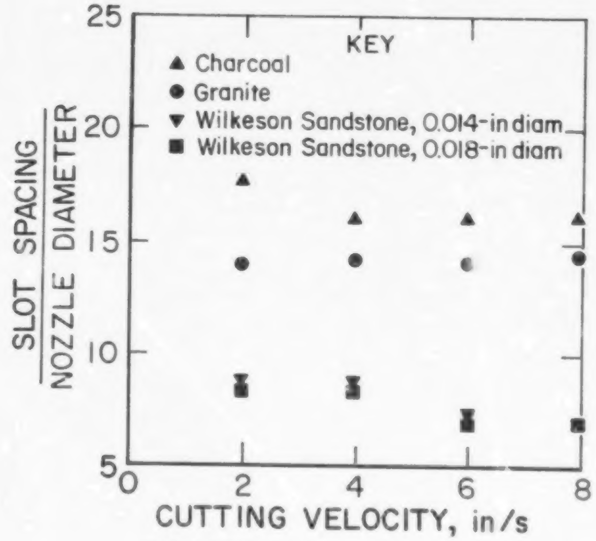
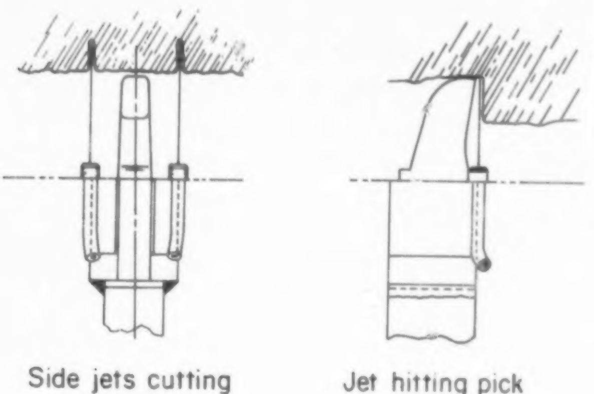


FIGURE 2. - Kerf spacing.



Side jets cutting ahead of pick

Jet hitting pick at contact point

FIGURE 3. - Mechanical cutting with water-jet assist.

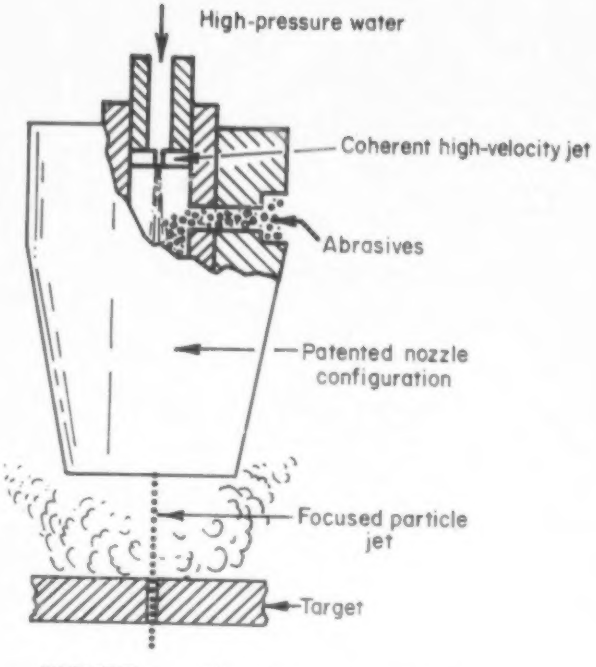
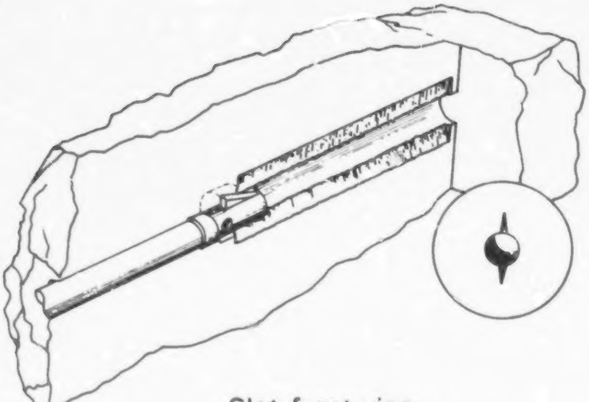

High-pressure water
Coherent high-velocity jet
Abrasives
Patented nozzle configuration
Focused particle jet
Target

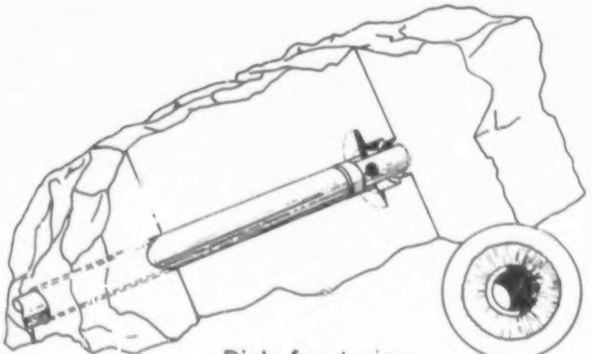
FIGURE 4. - Abrasive water-jet schematic.

makes hydraulic mining impractical. Mining with pure water jets makes economic sense only under special conditions, such as where the seam is on an angle and the material is friable (as in coal mining). It is, therefore, advantageous to identify applications where minimal material removal produces the desired results.

An example of "minimal removal" is disking and/or slotting of a drilled hole (fig. 5). In this case the water jet is used to create slots along the side of the hole. These slots allow the direction of fracture to be determined before blasting, enabling more efficient breakage of the rock. When the back of a hole is disked, "boot leg" is eliminated and more of the rock in a face is recovered.



Slot fracturing



Disk fracturing

FIGURE 5. - Water-jet slotting and disking.

In this example, the ability of a water jet to cut a rock without mechanical contact is more important than the energy required to do the cutting. This is because the minimal cut has a pronounced effect on the overall mining process. This method can be used to the best advantage by optimizing the configuration of the blast holes to take full advantage of the improved breakage.

WATER-JET CUTTING WITH MECHANICAL ASSIST

In this method, the water jet provides the principal means of cutting while the mechanical assist is used to break the rock left uncut by the jets. The thrust and torque of such a cutting device are much lower than for a similar mechanical cutter, but the power requirements are higher in many cases. Hence, the most appropriate applications are when thrust and torque reduction are of prime importance.

An example of this cutting method is a high-pressure water-jet drill (fig. 6). In this type of drill, the cutting water jets leave ridges, which are then broken off as the drill progresses. The drill requires thrusts of several hundred pounds; the reduced cutter loads extend operating life. This type of drill is especially useful in abrasive rock, when equipment must be light and maneuverable, when hand operation is required, and when a longer-than-seam-height drill is required. This latter application is one where low torque and thrust are critical, due to transmission around a curve.

Although this type of drill has many inherent advantages, the energy consumption and capital cost could be prohibitive. It is, therefore, critical to optimize the cutting process for a particular application.

MECHANICAL CUTTING WITH WATER-JET ASSIST

Water jets can be used to augment the cutting process of a mechanical cutter. This reduces the required cutting force and allows pick or cutter spacing to be increased, improving overall cutting performance. In addition, water jets improve the ability of a machine to efficiently cut harder rock. This method of cutting with water jets is particularly useful when machine size is not the critical factor, since most of the cutting is accomplished mechanically.

Large mining equipment for such applications includes longwall shearers, continuous miners, road headers, and raise and blind shaft borers. In this application the jet is used to directly assist the cutter (fig. 7). In underground tests, this equipment improved cutting, reduced dust and wear, and eliminated sparking.

To optimize this type of cutting system, it is necessary to determine the best method to directly assist only those cutters in contact with the rock. This is especially important in machines that employ a rotating drum, only a portion of which is actually in contact with the cutting face.

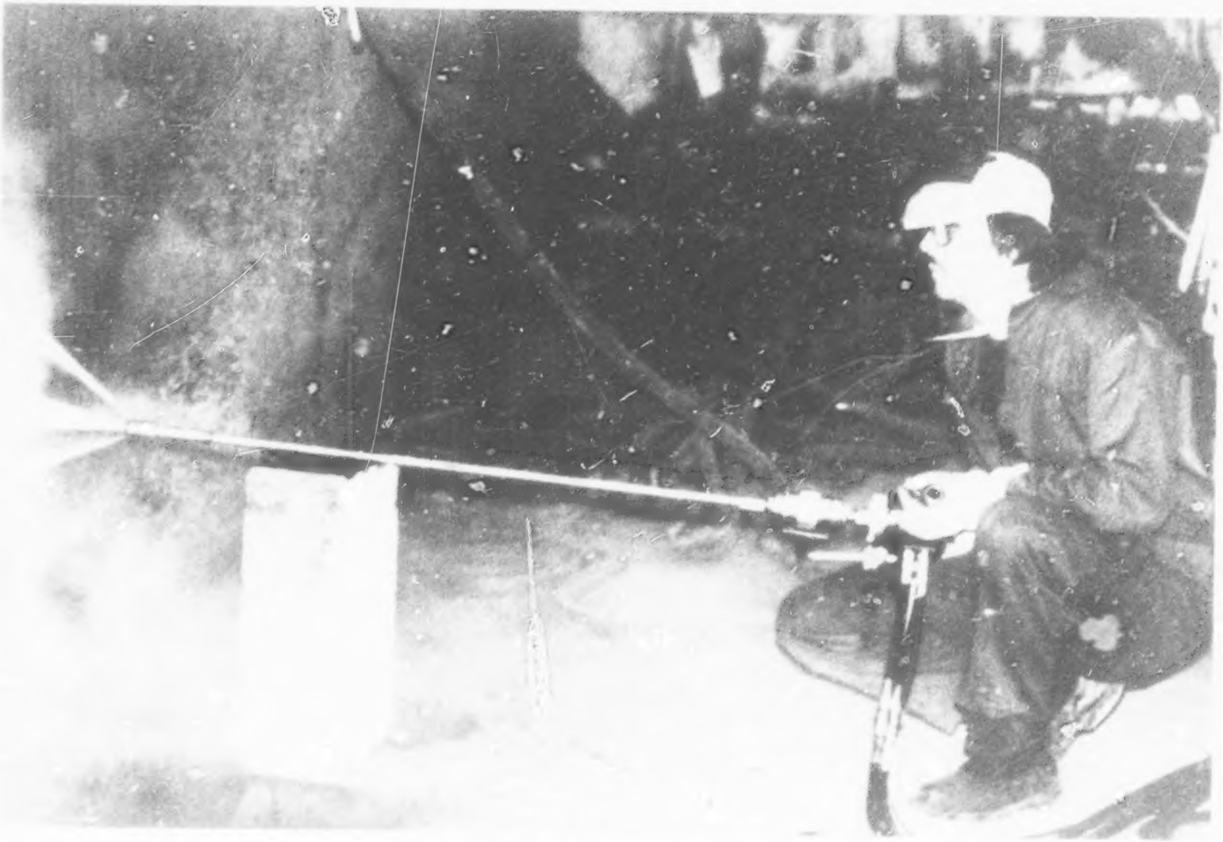


FIGURE 6. - Water-jet drill.

ABRASIVE WATER-JET CUTTING

The use of a water jet with an entrained abrasive allows a deep cut (up to 24 in) to be made in rock. The resulting slot can be used to isolate a portion of rock from the main body, enabling selective excavation.

Some applications of this technique are improved perimeter control, as shown in figure 8, selective mining, and roof and floor control. Optimization involves adjusting the abrasive water jet itself for the particular process, as well as integration of the technique with the entire mining or tunneling process.

WATER-JET OPTIMIZATION

All systems utilizing water jets must be optimized. This often means simply identifying the pressure and flow rate that most efficiently produce the desired result. In other cases, optimization involves reducing energy waste. The following subsections describe optimizations for some selective applications.

WATER-JET DRILL WITH MECHANICAL ASSIST

When using water jets as the primary cutting tool, the objective is to develop a drill with minimum mechanical assist. The drill should be capable of drilling effectively in all rocks. However, as a general rule for optimum performance, the harder the rock the higher the operating pressure.

To develop the drill, an acceptable horsepower level and a maximum allowable flow rate must be established. It is important to determine these parameters at the outset, since the available power determines the initial and operating cost of the equipment. Also, excessive water

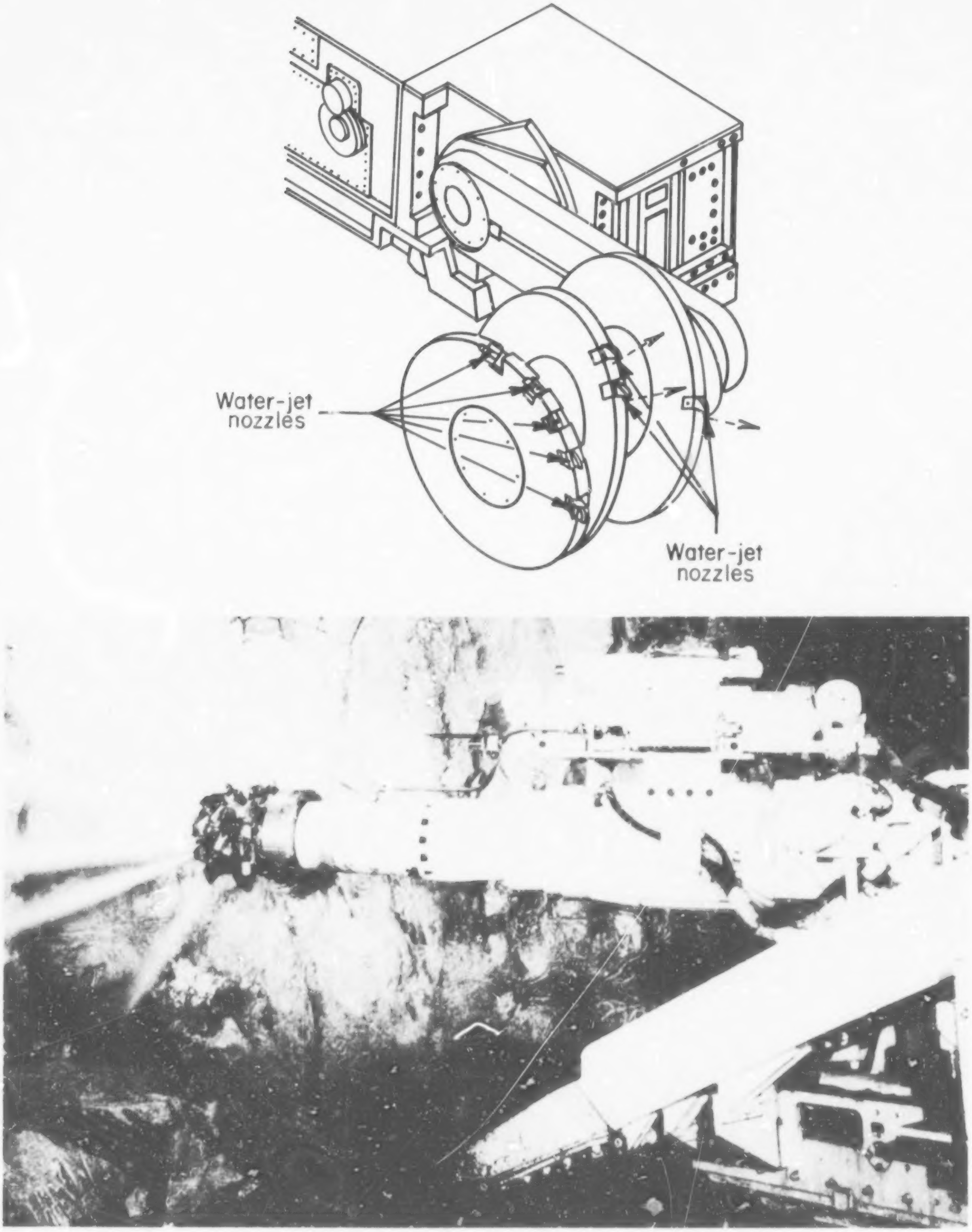

Water-jet nozzles
Water-jet nozzles

FIGURE 7. - Water-jet shearer and roadheader.

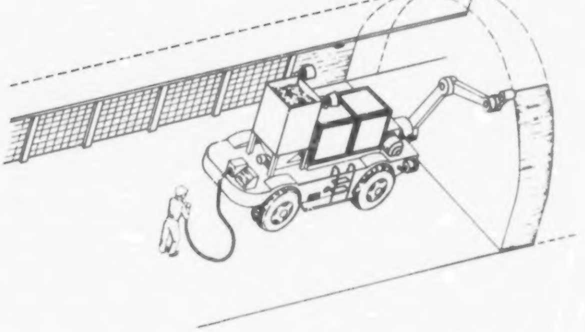


FIGURE 8. - Perimeter control with abrasive jet.

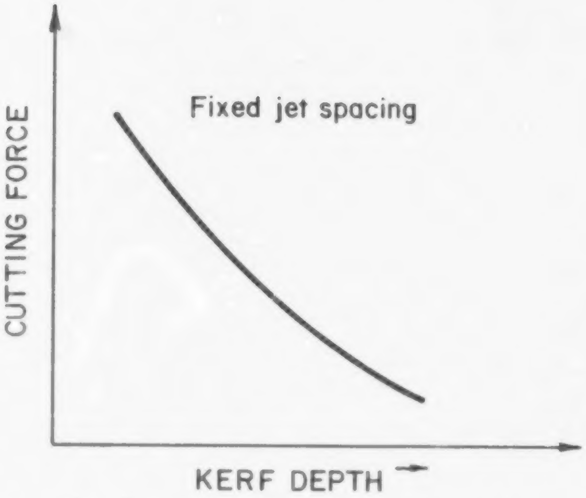


FIGURE 9. - Force versus groove depth.

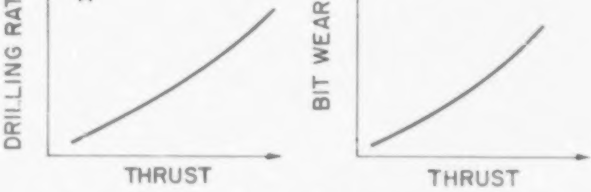


FIGURE 10. - Effect of thrust on drilling rate and wear (constant-diameter hole).

requirements can result in supply and disposal problems, as well as floor control problems. By setting these parameters, the range of available pressures can be determined. The actual pressure at which the drill is operated should be the minimum pressure required to obtain an acceptable cutting speed in a particular application. Minimizing the pressure increases the reliability of high-pressure components.

Optimizing drill performance only starts with establishing the operating pressure; the remainder of the process involves determining the most critical characteristics of the drill. This results from contradictory trends in the drill performance. For example, if the water jet is used to cut grooves which are then broken off by a mechanical cutter, groove depth must be maximized. As shown in figure 9, there is an inverse relationship between the depth of cut and the force needed to break the uncut ridge. However, it is not always possible to cut a deep kerf using available pumps. As a result, it may be necessary to use higher than desired drill thrust to achieve acceptable cutting.

A second important compromise in the drill design is the effect of increasing the thrust on the drill. The positive result is that the drill rate increases dramatically with thrust (fig. 10*A*). However, this advantage is countered by increased drill wear (fig. 10*B*). The wear rate increase can have important ramifications on the economics of the drilling process that offset the increased speed.

The optimization process can result in a drill that is close to being as energy efficient as a conventional drill, performing at comparable or better drilling rates while reducing bit wear by a factor of 4 or 5. Drills of this type have already been developed for roof bolting application, and hard-rock drills are currently being examined.

WATER-JET-ASSISTED MECHANICAL CUTTING

The application of water-jet-assisted mechanical cutting is widely being examined for improved performance of mining and tunneling machines. Two methods of applying the jet assist have been examined: direct assist on the bit and slotting between cutters.[2] In both methods the performance is optimized by maintaining a high power density in the jet at the rock. Retaining high power density on typical mining machines is not always easy.

Typical mining machines using either picks or disk cutters do not allow the jet to be close to the cutting surface. This has an adverse effect on the cutting effectiveness of the jet, as illustrated in figure 11. There is a dramatic decrease in depth with distance which adversely affects performance. This can be compensated for by increasing the jet pressure or diameter. Increasing either of these increases the power required for the machine. An alternate approach is to use small concentrations of polymer in the jet. This has been demonstrated[3] to increase jet coherence, and thus cutting effect with distance is improved. This could prove to be an efficient alternative to increasing the jet power and still achieving the desired decrease in cutting force.

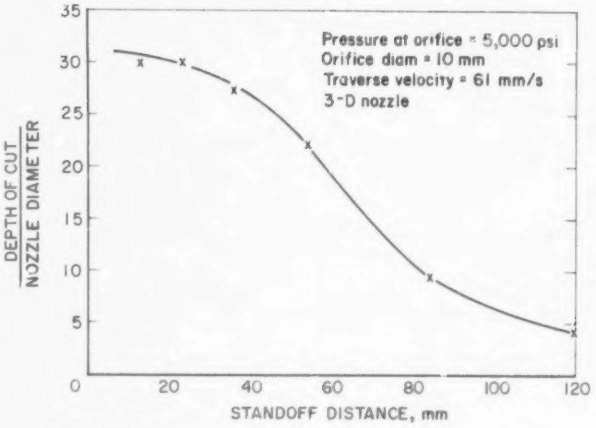


FIGURE 11. - Water-jet cutting effectiveness with standoff.

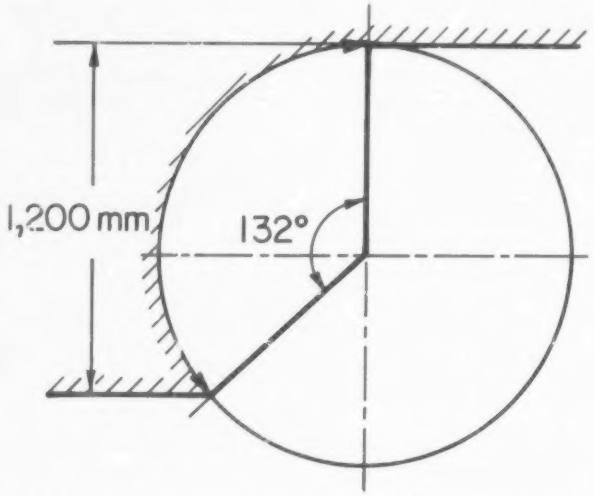


FIGURE 12. - Cutting drum contact area with rock.

In many mining machines only a portion of the cutters are actually in contact with the rock. Only a third of the cutting bits shown on the shearer drum (fig. 12) are cutting at any one time; during about two-thirds of the drum rotation the cutters are in the air. If all the cutters are continuously assisted with water jets, two-thirds of the energy is wasted. This problem can be eliminated by activating the jets as they come in contact with the rock. This can be achieved by segmented valves, which supply water to the segment of the head that is in contact with the rock. Examples of each are discussed below.

Flow Industries has developed a sequencing system for a milling type road header. The valving system is shown in figure 13. This particular arrangement was designed so that 1 to 16 segments in the head could be operated. Since this particular device was for development purposes, it had to operate at up to 50,000 psi. The mode of operation of this particular system follows:

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[2] Hennecke, J., and L. Baumann. Jet Assisted Tunnel Boring in Coal-Measure Strata. Paper in Fourth International Symposium on Jet Cutting Technology (Univ. Kent, Apr. 12-14, 1978). BHRA Fluid Engineering, Cranfield, Bedford, England, 1978, pp. J1 ff.

[3] Franz, N. C. Fluid Additives for Improving High Velocity Jet Cutting. Paper in First International Symposium on Jet Cutting Technology (Univ. Warwich, Apr. 5-7, 1972). BHRA Fluid Engineering, Cranfield, Bedford, England, 1972, pp. A7 ff.

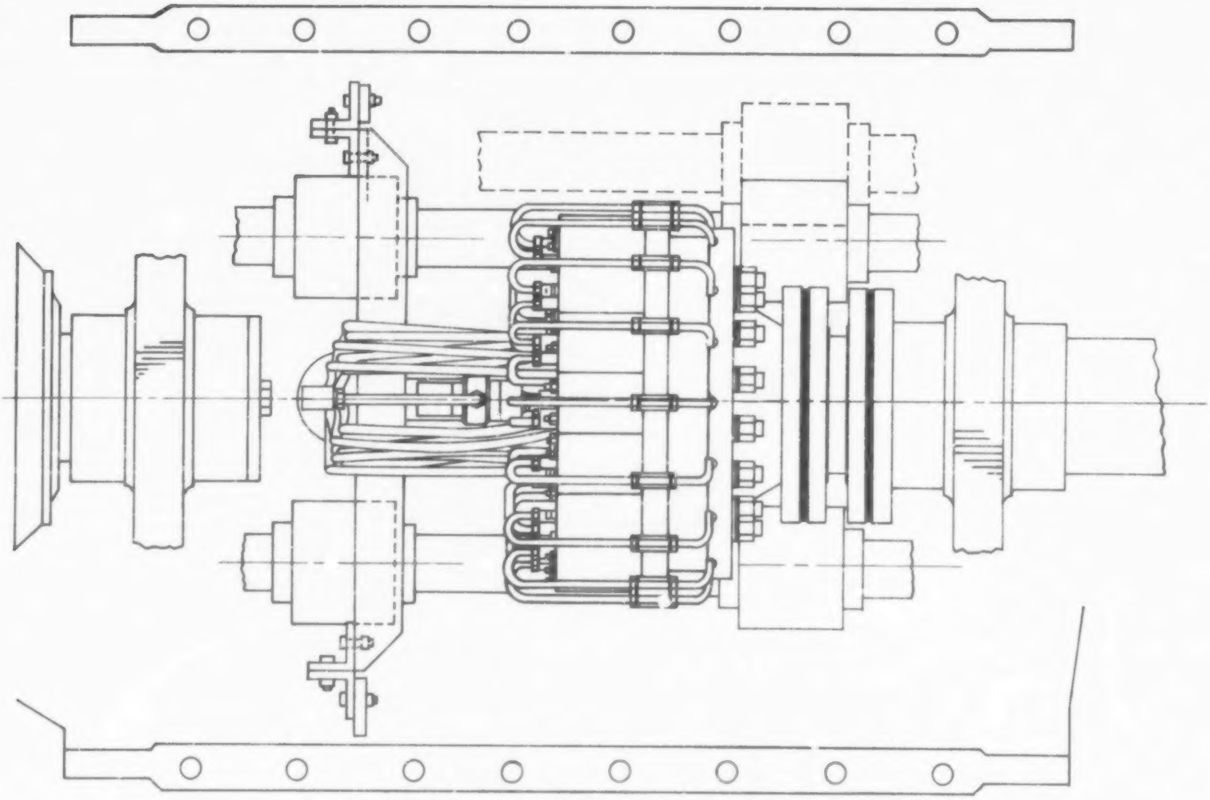

FIGURE 13. - Selecting valving arrangement.

1. Pressure is applied to all the valves. In this condition all the valves are closed.

2. The desired segments in the valve are opened to tank. This activates the valves in that segment.

3. As the cutting head is rotated, the valves get pressure as they leave the sections that close the flow to the nozzles. At the same time, as new valves enter the drained section, the valves are opened.

The fluid from each on-off valve is plumbed through the drive shaft to the nozzles in the appropriate quadrant. This is shown schematically in figure 14.

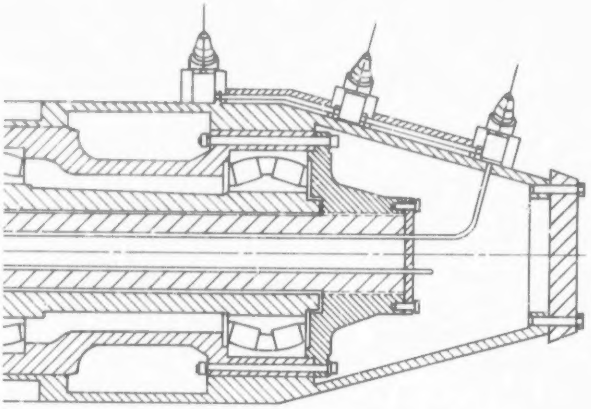

FIGURE 14. - Nozzle plumbing.

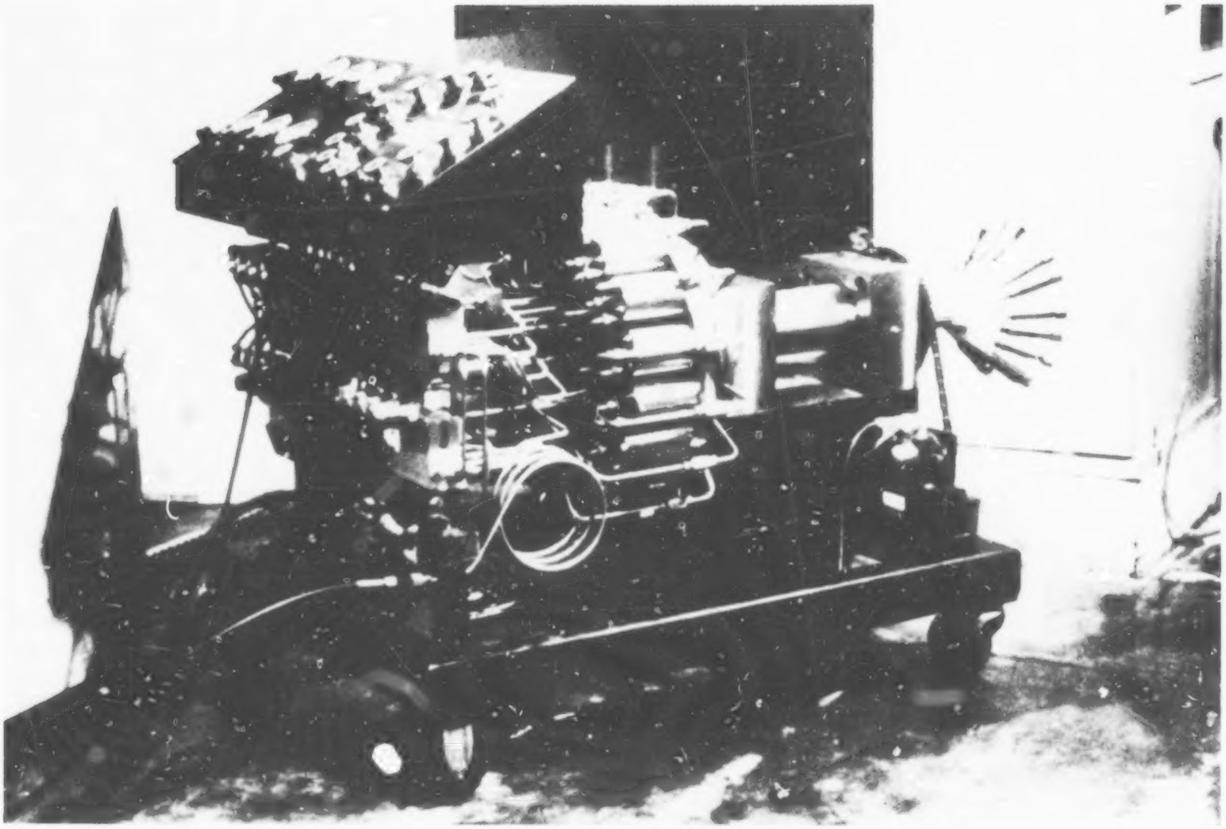

FIGURE 15. - Actual hardware of phasing system.

The actual hardware has been built and successfully tested. The equipment is shown in figure 15. This segmental control system is not practical in an actual machine because of the flexibility requirement. In an actual machine a far simpler, smaller, and more maintainable system can be developed.

A second approach to selective assist is to mount control valves directly in the cutter. Using such a device, the jet is activated when the cutter is loaded and shuts off when the load is removed. The valve shown schematically in figure 16 is opened by a fixed travel of the cutter. The jet in this particular case is an integral part of the cutter.

Both these control systems offer an efficient method of achieving the advantages of water-jet assist while minimizing the power requirements and operator safety and visibility.

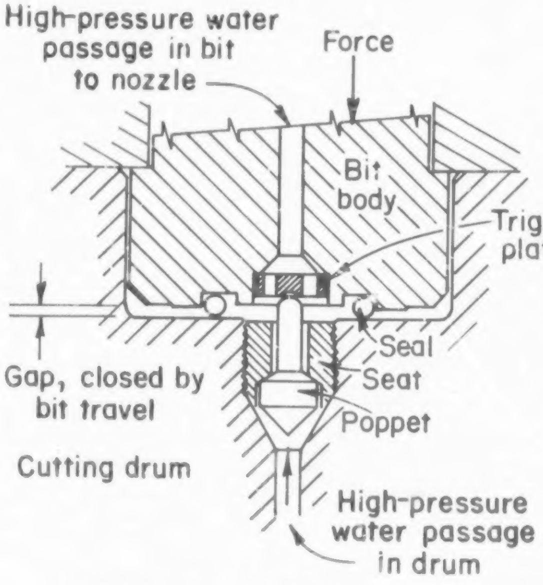
High-pressure water passage in bit to nozzle
Force
Bit body
Trigger plate
Seal
Seat
Poppet
Gap, closed by bit travel
Cutting drum
High-pressure water passage in drum

FIGURE 16. - Pick-activated valve.

CONCLUSIONS

Water jets used either alone, in combination with mechanical cutting, or with an entrained abrasive can effectively be used in a mining operation. The reduction in cutting force, dust generation, and machine vibration is beneficial for continuous cutting operations. The ability to slot rock can lead to improved blasting and ground control. Because of the varying methods of applying water jet, there is no good method of application. To use this technique it is important to examine the entire mining system. This allows for the opimum use of improved equipment or technique for a specific operation.

Once the area of application is identified from a system study, a parametric evaluation is required to determine the best operation conditions for the jet to achieve the desired performance. It is important to understand that no one operating condition meets all applications. To take full advantage of water jet at minimum energy consumption, it is necessary to deliver the jet power with minimum losses. In the case of many mining machines sequencing valves must be used to eliminate waste.

Water-jet technology is new to the mining industry. The techniques and equipment need to go from the laboratory into the field. After experience is gained with the equipment, optimization should become a simpler process.

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